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ABSTRACT:

The invention generally relates to a method and apparatus for taking an input signal, replicating it a number of times and modifying each of the replicas before routing them to respective output transducers such that a desired sound field is created. This sound field may comprise a directed beam, focussed beam or a simulated origin. In a first aspect, delays are added to sound channels to remove the effects of different travelling distances. In a second aspect, a delay is added to a video signal to account for the delays added to the sound channels. In a third aspect, different window functions are applied to each channel to give improved flexibility of use. In a fourth aspect, a smaller extent of transducers is used to output high frequencies than are used to output low frequencies. An array having a larger density of transducers near the centre is also provided. In a fifth aspect, a line of elongate transducers is provided to give good directivity in a plane. In a sixth aspect, sound beams are focussed in front or behind surfaces to give different beam widths and simulated origins. In a seventh aspect, a camera is used to indicate where sound is directed.

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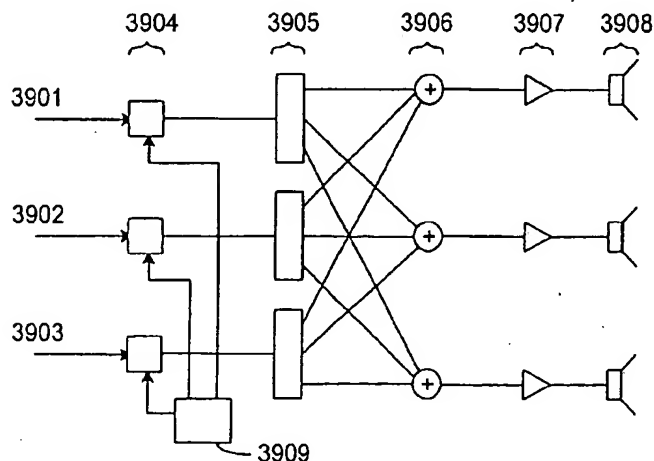
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(54) Title: **METHOD AND APPARATUS TO CREATE A SOUND FIELD**

(57) Abstract: The invention generally relates to a method and apparatus for taking an input signal, replicating it a number of times and modifying each of the replicas before routing them to respective output transducers such that a desired sound field is created. This sound field may comprise a directed beam, focussed beam or a simulated origin. In a first aspect, delays are added to sound channels to remove the effects of different travelling distances. In a second aspect, a delay is added to a video signal to account for the delays added to the sound channels. In a third aspect, different window functions are applied to each channel to give improved flexibility of use. In a fourth aspect, a smaller extent of transducers is used to output high frequencies than are used to output low frequencies. An array having a larger density of transducers near the centre is also provided. In a fifth aspect, a line of elongate transducers is provided to give good directivity in a plane. In a sixth aspect, sound beams are focussed in front or behind surfaces to give different beam widths and simulated origins. In a seventh aspect, a camera is used to indicate where sound is directed.



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## METHOD AND APPARATUS TO CREATE A SOUND FIELD

This invention relates to steerable acoustic antennae, and concerns in particular digital electronically-steerable acoustic antennae.

5        Phased array antennae are well known in the art in both the electromagnetic and the ultrasonic acoustic fields. They are less well known, but exist in simple forms, in the sonic (audible) acoustic area. These latter are relatively crude, and the invention seeks to provide improvements related to a superior audio acoustic array capable of being steered so as to direct its output more or less at will.

10        WO 96/31086 describes a system which uses a unary coded signal to drive a an array of output transducers. Each transducer is capable of creating a sound pressure pulse and is not able to reproduce the whole of the signal to be output.

      A first aspect of the present invention addresses the problem that can arise when multiple channels are output by a single array of output transducers with each  
15        channel being directed in a different direction. Due to the fact that each channel takes a different path to the listener, the channels can be audibly out of synchronism when they arrive at the listener's position.

      In accordance with the first aspect, there is provided a method of creating a sound field comprising a plurality of channels of sound using an array of output  
20        transducers, said method comprising:

      for each channel, selecting a first delay value in respect of each output transducer, said first delay value being chosen in accordance with the position in the array of the respective transducer;

      selecting a second delay value for each channel, said second delay value  
25        being chosen in accordance with the expected travelling distance of sound waves of that channel from said array to a listener;

      obtaining, in respect of each output transducer, a delayed replica of a signal representing each channel, each delayed replica being delayed by a value having a first component comprising said first delay value and a second component  
30        comprising said second delay value.

Also in accordance with the first aspect of the invention there is provided apparatus for creating a sound field comprising:

a plurality of inputs for a plurality of respective signals representing different sound channels;

5 an array of output transducers;

replication means arranged to obtain, in respect of each output transducer, a replica of each respective input signal;

first delay means arranged to delay each replica of each signal by a respective first delay value chosen in accordance with the position in the array of the respective  
10 output transducer;

second delay means arranged to delay each replica of each signal by a second delay value chosen for each channel in accordance with the expected travelling distance of sound waves of that channel from the array to a listener.

Thus, there is provided a method and apparatus for applying two types of  
15 delay to each sound channel to alleviate the effect of different travelling distances for each channel.

A second aspect of the invention addresses the problem that arises in audio-visual applications of the array of output transducers. Due to the various delays that often need to be applied to the channels to create the desired effects, the sound  
20 channels can lag behind the video pictures noticeably.

According to the second aspect of the invention, there is provided a method of providing temporal correspondence between pictures and sound in an audio-visual presentation using an array of output transducers to reproduce the sound content comprising a plurality of channels, said method comprising:

25 delaying, in respect of each output transducer, a replica of each signal representing a sound channel by a respective audio delay value;

delaying a video signal by a video delay value calculated so corresponding video pictures are displayed at substantially the time the temporally corresponding sound channels reach the listener.

30 Further, in accordance with the second aspect of the present invention, there

is provided apparatus to provide temporal correspondence between pictures and a plurality of sound channels in an audio-visual presentation comprising:

an array of output transducers;

- replication and delay means arranged to obtain, in respect of each output
- 5 transducer, a delayed replica of each signal representing a sound channel;
- video delay means arranged to delay a corresponding video signal by a video delay value calculated so corresponding video pictures are displayed at substantially the time the temporally corresponding sound channels reach the listener.

This aspect of the invention thus allows the video and sound channels to

10 arrive at the viewer/listener at the correct time (ie in temporal correspondence with one another)

A third aspect of the present invention addresses the problem that different sound channels may have different contents and thus there are different needs in terms of the directivity to be achieved by any particular beam representing a sound

15 channel.

Accordingly, the third aspect of the invention provides a method of creating a sound field comprising a plurality of channels of sound using an array of output transducers, said method comprising:

- for each channel, obtaining, in respect of each output transducer, a replica of a
- 20 signal representing said channel so as to obtain a set of replica signals for each channel;

applying a first window function to a first set of replica signals originating from a first sound channel signal;

- applying a second, different, window function to a second set of replica
- 25 signals originating from a second sound channel signal.

Further, in accordance with the third aspect of the invention, there is provided apparatus to create a sound field comprising a plurality of channels of sound, comprising:

an array of output transducers;

- 30 replication means for providing, in respect of each output transducer, a replica

of a signal representing each of said plurality of channels;

          windowing means for applying a first window function to a first set of replica signals originating from a first sound channel signal and for applying a second, different, window function to a second set of replica signals originating from a  
5 second channel signal.

          This aspect therefore allows different window functions to be applied to different sound channels giving a more desirable sound field and making it easier to adjust the volume of each sound channel independently.

          A fourth aspect of the invention addresses the problem that a large array is  
10 required to direct low frequencies whereas a smaller array can direct high frequencies to the same accuracy. Further, low frequencies require higher power than high frequencies.

          In accordance with the fourth aspect of the invention there is provided a method of creating a sound field using an array of output transducers, said method  
15 comprising:

          dividing an input signal into at least a low frequency component and a high frequency component;

          using output transducers spanning a first portion of the array to output said low frequency component; and

20        using output transducers spanning a second portion of said array smaller than said first portion to output said high frequency component.

          Further in accordance with the fourth aspect of the invention there is provided apparatus for creating a sound field comprising:

          an array of output transducers wherein in a first area of the array the output  
25 transducers are more densely packed than in the remainder of said array.

          This aspect therefore allows all the frequencies to be output with the desired directivity using an efficient number of output transducers.

          A fifth aspect of the invention relates to an efficient configuration of array which can direct sound substantially within a desired plane.

30        In accordance with the fifth aspect of the invention there is provided an array

of output transducers positioned next to each other in a line; wherein each of said output transducers has a dimension in the direction perpendicular to said line larger than the dimension parallel to said line.

The above described configuration is particularly useful since the sound is  
5 primarily concentrated in a plane extending horizontally out of the front of the array. The concentration to a plane is achieved due to the elongate nature of the individual transducers and the directivity is achieved due to the plurality of transducers in the array.

The sixth aspect of the invention addresses the need to direct narrow or broad  
10 beams to a defined position using reflective or resonant surfaces in accordance with a users desire.

In accordance with the sixth aspect of the present invention there is provided  
A method of causing plural input signals representing respective channels to appear to emanate from respective different positions in space, said method comprising:

15 providing a sound reflective or resonant surface at each of said positions in space;

providing an array of output transducers distal from said positions in space;

and

directing, using said array of output transducers, sound waves of each channel  
20 towards the respective position in space to cause said sound waves to be re-transmitted by said reflective or resonant surface, said sound waves being focussed at a position in space in front of, or behind, said reflective or resonant surface;

said step of directing comprising:

obtaining, in respect of each transducer, a delayed replica of each input signal  
25 delayed by a respective delay selected in accordance with the position in the array of the respective output transducer and said respective focus position such that the sound waves of the channel are directed towards the focus position in respect of that channel;

summing, in respect of each transducer, the respective delayed replicas of  
30 each input signal to produce an output signal; and



routing the output signals to the respective transducers.

Further in accordance with the sixth aspect of the present invention there is provided an apparatus for causing plural input signals representing respective channels to appear to emanate from respective different positions in space, said

5 apparatus comprising:

a sound reflective or resonant surface at each of said positions in space;

an array of output transducers distal from said positions in space; and

a controller for directing, using said array of output transducers, sound waves of each channel towards that channel's respective position in space such that said

10 sound waves are re-transmitted by said reflective or resonant surface, said sound waves being focussed at a position in space in front of, or behind, said reflective or resonant surface;

said controller comprising:

replication and delay means arranged to obtain, in respect of each transducer,

15 a delayed replica of the input signal delayed by a respective delay selected in accordance with the position in the array of the respective output transducer and the respective focus position such that the sound waves of the channel are directed towards the focus position in respect of that input signal;

20 adder means arranged to sum, in respect of each transducer, the respective delayed replicas of each input signal to produce an output signal; and

means to route the output signals to the respective transducers such that the channel sound waves are directed towards the focus position in respect of that input signal.

The sixth aspect of the invention allows a narrow or broad beam to be re-  
25 transmitted in accordance with the focus position being chosen behind or in front of the reflector/resonator.

The seventh aspect of the invention addresses the problem that it can be difficult to determine exactly where sound is directed or focussed and there is a requirement for an intuitive method which allows an operator to control (with  
30 feedback) where the sound is directed or focussed.

In accordance with the seventh aspect of the present invention there is provided a method of selecting a direction in which to focus sound, said method comprising;

pointing a video camera in the desired direction, using the viewfinder or other  
5 screen means to determine if the direction is that desired;

calculating a plurality of signal delays to be applied to a set of replicas of an input signal so as to direct sound in the selected direction.

Further in accordance with the seventh aspect of the present invention there is provided a method of determining where sound is directed, said method comprising:

10 automatically adjusting the direction in which a video camera points in accordance with the direction in which sound is directed;

discerning from the viewfinder or other screen means which direction the camera is pointing in.

Furthermore in accordance with the seventh aspect of the present invention  
15 there is provided an apparatus for setting up or monitoring a sound field comprising:

an array of output transducers;

a directable video camera;

means controlling said array of output transducers and said video camera such that said video camera points in the same direction as a sound beam from said array  
20 is directed.

The seventh aspect of the invention thus allows a user to determine where sound is directed in an intuitive and easy manner.

Generally, the invention is applicable to a preferably fully digital steerable  
25 acoustic phased array antenna (a Digital Phased-Array Antennae, or DPAA) system comprising a plurality of spatially-distributed sonic electroacoustic transducers (SETs) arranged in a two-dimensional array and each connected to the same digital signal input via an input signal Distributor which modifies the input signal prior to feeding it to each SET in order to achieve the desired directional effect.

30 The various possibilities inherent in this, and the versions that are actually

preferred, will be seen from the following:-

The SETs are preferably arranged in a plane or curved surface (a Surface), rather than randomly in space. They may also, however, be in the form of a 2-dimensional stack of two or more adjacent sub-arrays - two or more closely-spaced  
5 parallel plane or curved surfaces located one behind the next.

Within a Surface the SETs making up the array are preferably closely spaced, and ideally completely fill the overall antenna aperture. This is impractical with real circular-section SETs but may be achieved with triangular, square or hexagonal section SETs, or in general with any section which tiles the plane. Where the SET  
10 sections do not tile the plane, a close approximation to a filled aperture may be achieved by making the array in the form of a stack of arrays - ie, three-dimensional - where at least one additional Surface of SETs is mounted behind at least one other such Surface, and the SETs in the or each rearward array radiate between the gaps in the frontward array(s).

15 The SETs are preferably similar, and ideally they are identical. They are, of course, sonic - that is, audio - devices, and most preferably they are able uniformly to cover the entire audio band from perhaps as low as (or lower than) 20Hz, to as much as 20KHz or more (the Audio Band). Alternatively, there can be used SETs of different sonic capabilities but together covering the entire range desired. Thus,  
20 multiple different SETs may be physically grouped together to form a composite SET (CSET) wherein the groups of different SETs together can cover the Audio Band even though the individual SETs cannot. As a further variant, SETs each capable of only partial Audio Band coverage can be not grouped but instead scattered throughout the array with enough variation amongst the SETs that the array as a  
25 whole has complete or more nearly complete coverage of the Audio Band.

An alternative form of CSET contains several (typically two) identical transducers, each driven by the same signal. This reduces the complexity of the required signal processing and drive electronics while retaining many of the advantages of a large DPAA. Where the position of a CSET is referred to  
30 hereinafter, it is to be understood that this position is the centroid of the CSET as a

whole, i.e. the centre of gravity of all of the individual SETs making up the CSET.

Within a Surface the spacing of the SETs or CSET (hereinafter the two are denoted just by SETs) - that is, the general layout and structure of the array and the way the individual transducers are disposed therein - is preferably regular, and their  
5 distribution about the Surface is desirably symmetrical. Thus, the SETs are most preferably spaced in a triangular, square or hexagonal lattice. The type and orientation of the lattice can be chosen to control the spacing and direction of side-lobes.

Though not essential, each SET preferably has an omnidirectional  
10 input/output characteristic in at least a hemisphere at all sound wavelengths which it is capable of effectively radiating (or receiving).

Each output SET may take any convenient or desired form of sound radiating device (for example, a conventional loudspeaker), and though they are all preferably the same they could be different. The loudspeakers may be of the type known as  
15 pistonic acoustic radiators (wherein the transducer diaphragm is moved by a piston) and in such a case the maximum radial extent of the piston-radiators (eg, the effective piston diameter for circular SETs) of the individual SETs is preferably as small as possible, and ideally is as small as or smaller than the acoustic wavelength of the  
20 highest frequency in the Audio Band (eg in air, 20KHz sound waves have a wavelength of approximately 17mm, so for circular pistonic transducers, a maximum diameter of about 17mm is preferable, with a smaller size being preferred to ensure omnidirectionality).

The overall dimensions of the or each array of SETs in the plane of the array are very preferably chosen to be as great as or greater than the acoustic wavelength in  
25 air of the lowest frequency at which it is intended to significantly affect the polar radiation pattern of the array. Thus, if it is desired to be able to beam or steer frequencies as low as 300Hz, then the array size, in the direction at right angles to each plane in which steering or beaming is required, should be at least  $c_s / 300 \approx 1.1$  metre (where  $c_s$  is the acoustic sound speed).

30 The invention is applicable to fully digital steerable sonic/ audible acoustic

phased array antenna system, and while the actual transducers can be driven by an analogue signal most preferably they are driven by a digital power amplifier. A typical such digital power amplifier incorporates: a PCM signal input; a clock input (or a means of deriving a clock from the input PCM signal); an output clock, which  
5 is either internally generated, or derived from the input clock or from an additional output clock input; and an optional output level input, which may be either a digital (PCM) signal or an analogue signal (in the latter case, this analogue signal may also provide the power for the amplifier output). A characteristic of a digital power amplifier is that, before any optional analogue output filtering, its output is discrete  
10 valued and stepwise continuous, and can only change level at intervals which match the output clock period. The discrete output values are controlled by the optional output level input, where provided. For PWM-based digital amplifiers, the output signal's average value over any integer multiple of the input sample period is representative of the input signal. For other digital amplifiers, the output signal's  
15 average value tends towards the input signal's average value over periods greater than the input sample period. Preferred forms of digital power amplifier include bipolar pulse width modulators, and one-bit binary modulators.

The use of a digital power amplifier avoids the more common requirement - found in most so-called "digital" systems - to provide a digital-to-analogue converter  
20 (DAC) and a linear power amplifier for each transducer drive channel, and therefore the power drive efficiency can be very high. Moreover, as most moving coil acoustic transducers are inherently inductive, and mechanically act quite effectively as low pass filters, it may be unnecessary to add elaborate electronic low-pass filtering between the digital drive circuitry and the SETs. In other words, the SETs can be  
25 directly driven with digital signals.

The DPAA has one or more digital input terminals (Inputs). When more than one input terminal is present, it is necessary to provide means for routing each input signal to the individual SETs.

This may be done by connecting each of the inputs to each of the SETs *via*  
30 one or more input signal Distributors. At the most basic, an input signal is fed to a

single Distributor, and that single Distributor has a separate output to each of the SETs (and the signal it outputs is suitably modified, as discussed hereinafter, to achieve the end desired). Alternatively, there may be a number of similar Distributors, each taking the, or part of the, input signal, or separate input signals, and then each providing a separate output to each of the SETs (and in each case the signal it outputs is suitably modified, with the Distributor, as discussed hereinafter, to achieve the end desired). In this latter case - a plurality of Distributors each feeding all the SETs - the outputs from each Distributor to any one SET have to be combined, and conveniently this is done by an adder circuit prior to any further modification the resultant feed may undergo.

The Input terminals preferably receive one or more digital signals representative of the sound or sounds to be handled by the DPAA (Input Signals). Of course, the original electrical signal defining the sound to be radiated may be in an analogue form, and therefore the system of the invention may include one or more analogue-to-digital converters (ADCs) connected each between an auxiliary analogue input terminal (Analogue Input) and one of the Inputs, thus allowing the conversion of these external analogue electrical signals to internal digital electrical signals, each with a specific (and appropriate) sample rate  $F_s$ . And thus, within the DPAA, beyond the Inputs, the signals handled are time-sampled quantized digital signals representative of the sound waveform or waveforms to be reproduced by the DPAA.

The DPAA of the invention incorporates a Distributor which modifies the input signal prior to feeding it to each SET in order to achieve the desired directional effect. A Distributor is a digital device, or piece of software, with one input and multiple outputs. One of the DPAA's Input Signals is fed into its input. It preferably has one output for each SET; alternatively, one output can be shared amongst a number of the SETs or the elements of a CSET. The Distributor sends generally differently modified versions of the input signal to each of its outputs. The modifications can be either fixed, or adjustable using a control system. The modifications carried out by the distributor can comprise applying a signal delay, applying amplitude control and/or adjustably digitally filtering. These modifications

may be carried out by signal delay means (SDM), amplitude control means (ACM) and adjustable digital filters (ADFs) which are respectively located within the Distributor. It is to be noted that the ADFs can be arranged to apply delays to the signal by appropriate choice of filter coefficients. Further, this delay can be made  
5 frequency dependent such that different frequencies of the input signal are delayed by different amounts and the filter can produce the effect of the sum of any number of such delayed versions of the signal. The terms "delaying" or "delayed" used herein should be construed as incorporating the type of delays applied by ADFs as well as SDMs. The delays can be of any useful duration including zero, but in general, at  
10 least one replicated input signal is delayed by a non-zero value.

The signal delay means (SDM) are variable digital signal time-delay elements. Here, because these are not single-frequency, or narrow frequency-band, *phase shifting* elements but true time-delays, the DPAA will operate over a broad frequency band (eg the Audio Band). There may be means to adjust the delays  
15 between a given input terminal and each SET, and advantageously there is a separately adjustable delay means for each Input/SET combination.

The minimum delay possible for a given digital signal is preferably as small or smaller than  $T_s$ , that signal's sample period; the maximum delay possible for a given digital signal should preferably be chosen to be as large as or larger than  $T_c$ , the  
20 time taken for sound to cross the transducer array across its greatest lateral extent,  $D_{max}$ , where  $T_c = D_{max} / c_s$ , where  $c_s$  is the speed of sound in air. Most preferably, the smallest incremental change in delay possible for a given digital signal should be no larger than  $T_s$ , that signal's sample period. Otherwise, interpolation of the signal is necessary.

25 The amplitude control means (ACM) is conveniently implemented as digital amplitude control means for the purposes of gross beam shape modification. It may comprise an amplifier or alternator so as to increase or decrease the magnitude of an output signal. Like the SDM, there is preferably an adjustable ACM for each Input/SET combination. The amplitude control means is preferably arranged to  
30 apply differing amplitude control to each signal output from the Distributor so as to

counteract for the fact that the DPAA is of finite size by using a window function. This is conveniently achieved by normalising the magnitude of each output signal in accordance with a predefined curve such as a Gaussian curve or a raised cosine curve. Thus, in general, output signals destined for SETs near the centre of the array  
5 will not be significantly affected but those near to the perimeter of the array will be attenuated according to how near to the edge of the array they are.

Another way of modifying the signal uses digital filters (ADF) whose group delay and magnitude response vary in a specified way as a function of frequency (rather than just a simple time delay or level change) - simple delay elements may be  
10 used in implementing these filters to reduce the necessary computation. This approach allows control of the DPAA radiation pattern as a function of frequency which allows control of the radiation pattern of the DPAA to be adjusted separately in different frequency bands (which is useful because the size in wavelengths of the DPAA radiating area, and thus its directionality, is otherwise a strong function of  
15 frequency). For example, for a DPAA of say 2m extent its low frequency cut-off (for directionality) is around the 150Hz region, and as the human ear has difficulty in determining directionality of sounds at such a low frequency it may be more useful not to apply "beam-steering" delays and amplitude weighting at such low frequencies but instead to go for an optimized output level. Additionally, the use of filters may  
20 also allow some compensation for unevenness in the radiation pattern of each SET.

The SDM delays, ACM gains and ADF coefficients can be fixed, varied in response to User input, or under automatic control. Preferably, any changes required while a channel is in use are made in many small increments so that no discontinuity is heard. These increments can be chosen to define predetermined "roll-off" and  
25 "attack" rates which describe how quickly the parameters are able to change.

Where more than one Input is provided - ie there are  $I$  inputs numbered 1 to  $I$  and where there are  $N$  SETs, numbered 1 to  $N$ , it is preferable to provide a separate and separately-adjustable delay, amplitude control and/or filter means  $D_{in}$  (where  $I = 1$  to  $I$ ,  $n = 1$  to  $N$ , between each of the  $I$  inputs and each of the  $N$  SETs) for each  
30 combination. For each SET there are thus  $I$  delayed or filtered digital signals, one



from each of the Inputs *via* the separate Distributor, to be combined before application to the SET. There are in general  $N$  separate SDMs, ACMs and/or ADFs in each Distributor, one for each SET. As noted above, this combination of digital signals is conveniently done by digital algebraic addition of the  $I$  separate delayed signals - ie the signal to each SET is a linear combination of separately modified signals from each of the  $I$  Inputs. The requirement to perform digital addition of signals originating from more than one Input means that the digital sampling rate converters (DSRCs) may need to be used, to synchronize these external signals, as it is generally not meaningful to perform digital addition on two or more digital signals with different clock rates and/or phases.

The DPAA system may be used with a remote-control handset (Handset) that communicates with the DPAA electronics (*via* wires, or radio or infra-red or some other wireless technology) over a distance (ideally from anywhere in the listening area of the DPAA), and provides manual control over all the major functions of the DPAA. Such a control system would be most useful to provide the following functions:

- 1) selection of which Input(s) are to be connected to which Distributor, which might also be termed a "Channel";
- 2) control of the focus position and/or beam shape of each Channel;
- 3) control of the individual volume-level settings for each Channel; and
- 4) an initial parameter set-up using the Handset having a built-in microphone (see later).

There may also be:

means to interconnect two or more such DPAA's in order to coordinate their radiation patterns, their focussing and their optimization procedures;

means to store and recall sets of delays (for the DDGs) and filter coefficients (for the ADFs);

The invention will be further described, by way of non-limitative example only, with reference to the accompanying schematic drawings, in which:-

Figure 1 shows a representation of a simple single-input apparatus;

Figure 2 is a block diagram of a multiple-input apparatus;

Figure 3 is a block diagram of a general purpose Distributor;

Figure 4 is a block diagram of a linear amplifier and a digital amplifier used in preferred embodiments of the present invention;

5        Figure 5 shows the interconnection of several arrays with common control and input stages;

Figure 6 shows a Distributor in accordance with the first aspect of the present invention;

Figures 7A to 7D show four types of sound field which may be achieved  
10    using the apparatus of the first aspect of the present invention;

Figure 8 shows three different beam paths obtained when three sound channels are directed in different directions in a room;

Figure 9 shows an apparatus for applying a delay to each channel to account for different travelling distances;

15        Figure 10 shows an apparatus for delaying a video signal in accordance with the delays applied to the audio channels;

Figures 11A to 11D show various window functions used to explain the third aspect of the present invention;

Figure 12 shows an apparatus for applying different window functions to  
20    different channels;

Figure 13 is a block diagram showing apparatus capable of shaping different frequencies in different ways;

Figure 14 shows an apparatus for routing different frequency bands to separate output transducers;

25        Figure 15 shows an apparatus for routing different frequency bands to overlapping sets of output transducers;

Figure 16 shows a front view of an array with symbols representing the frequency bands which each transducer outputs;

Figure 17 shows an array of output transducers having a denser region of  
30    transducers near the centre, in accordance with the fourth aspect of the invention;

Figure 18 shows a single transducer having an elongate structure;

Figure 19 shows an array of the transducers shown in Figure 18;

Figure 20 shows a plan view of an array of output transducers and reflective/resonant screens to achieve a surround sound effect;

5        Figure 21 shows a plan view of an array of transducers and reflective/resonant surfaces, with beam patterns being reflected from the surfaces;

Figure 22 shows a side view of an array having a video camera attached in accordance with the seventh aspect of the invention;

Figure 23 is a drawing of a typical set-up of a loudspeaker system in  
10    accordance with the first aspect of the present invention;

Figure 24 is a block diagram of a first part of a digital loudspeaker system in accordance with a preferred embodiment of the first aspect of the present invention;

Figure 25 is a block diagram of a second part of a digital loudspeaker system in accordance with a preferred embodiment of the first aspect of the present  
15    invention; and

Figure 26 is a block diagram of a third part of a digital loudspeaker system in accordance with a preferred embodiment of the first aspect of the present invention.

The description and Figures provided hereinafter necessarily describe the  
20    invention using block diagrams, with each block representing a hardware component or a signal processing step. The invention could, in principle, be realised by building separate physical components to perform each step, and interconnecting them as shown. Several of the steps could be implemented using dedicated or programmable integrated circuits, possibly combining several steps in one circuit. It will be  
25    understood that in practice it is likely to be most convenient to perform several of the signal processing steps in software, using Digital Signal Processors (DSPs) or general purpose microprocessors. Sequences of steps could then be performed by separate processors or by separate software routines sharing a microprocessor, or be combined into a single routine to improve efficiency.

30        The Figures generally only show audio signal paths; clock and control

connections are omitted for clarity unless necessary to convey the idea. Moreover, only small numbers of SETs, Channels, and their associated circuitry are shown, as diagrams become cluttered and hard to interpret if the realistically large numbers of elements are included.

- 5        Before the respective aspects of the present invention are described, it is useful to describe embodiments of the apparatus which are suitable for use in accordance with any of the respective aspects.

      The block diagram of Figure 1 depicts a simple DPAA. An input signal (101) feeds a Distributor (102) whose many (6 in the drawing) outputs each connect  
10 through optional amplifiers (103) to output SETs (104) which are physically arranged to form a two-dimensional array (105). The Distributor modifies the signal sent to each SET to produce the desired radiation pattern. There may be additional processing steps before and after the Distributor, as illustrated later.

- Figure 2 shows a DPAA with two input signals (501,502) and three  
15 Distributors (503-505). Distributor 503 treats the signal 501, whereas both 504 and 505 treat the input signal 502. The outputs from each Distributor for each SET are summed by adders (506), and pass through amplifiers 103 to the SETs 104.

- Figure 3 shows the components of a Distributor. It has a single input signal (101) coming from the input circuitry and multiple outputs (802), one for each SET  
20 or group of SETs. The path from the input to each of the outputs contains a SDM (803) and/or an ADF (804) and/or an ACM (805). If the modifications made in each signal path are similar, the Distributor can be implemented more efficiently by including global SDM, ADF and/or ACM stages (806-808) before splitting the signal. The parameters of each of the parts of each Distributor can be varied under  
25 User or automatic control. The control connections required for this are not shown.

- Figure 4 shows possible power amplifier configurations. In one option, the input digital signal (1001), possibly from a Distributor or adder, passes through a DAC (1002) and a linear power amplifier (1003) with an optional gain/volume control input (1004). The output feeds a SET or group of SETs (1005). In a  
30 preferred configuration, this time illustrated for two SET feeds, the inputs (1006)

directly feed digital amplifiers (1007) with optional global volume control input (1008). The global volume control inputs can conveniently also serve as the power supply to the output drive circuitry. The discrete-valued digital amplifier outputs optionally pass through analogue low-pass filters (1009) before reaching the SETs  
5 (1005).

Figure 5 illustrates the interconnection of three DPAA's (1401). In this case, the inputs (1402), input circuitry (1403) and control systems (1404) are shared by all three DPAA's. The input circuitry and control system could either be separately housed or incorporated into one of the DPAA's, with the others acting as slaves.  
10 Alternatively, the three DPAA's could be identical, with the redundant circuitry in the slave DPAA's merely inactive. This set-up allows increased power, and if the arrays are placed side by side, better directivity at low frequencies.

The apparatus of Figures 6 and 7A to 7D has the general structure shown in Figure 1. Figure 6 shows a preferable Distributor (102) in further detail.

15 As can be seen from Figure 6, the input signal (101) is routed to a replicator (1504) by means of an input terminal (1514). The replicator (1504) has the function of copying the input signal a pre-determined number of times and providing the same signal at said pre-determined number of output terminals (1518). Each replica of the input signal is then supplied to the means (1506) for modifying the replicas. In  
20 general, the means (1506) for modifying the replicas includes signal delay means (1508), amplitude control means (1510) and adjustable digital filter means (1512). However, it should be noted that the amplitude control means (1510) is purely optional. Further, one or other of the signal delay means (1508) and adjustable digital filter (1512) may also be dispensed with. The most fundamental function of  
25 the means (1506) to modify replicas is to provide that different replicas are in some sense delayed by generally different amounts. It is the choice of delays which determines the sound field achieved when the output transducers (104) output the various delayed versions of the input signal (101). The delayed and preferably otherwise modified replicas are output from the Distributor (102) via output  
30 terminals (1516).

As already mentioned, the choice of respective delays carried by each signal delay means (1508) and/or each adjustable digital filter (1512) critically influences the type of sound field which is achieved. In general, there are four particularly advantageous sound fields which can be linearly combined.

5

#### First Sound Field

A first sound field is shown in Figure 7A.

The array (105) comprising the various output transducers (104) is shown in  
10 plan view. Other rows of output transducers may be located above or below the illustrated row.

The delays applied to each replica by the various signal delay means (508) are set to be the same value, eg 0 (in the case of a plane array as illustrated), or to values that are a function of the shape of the Surface (in the case of curved surfaces). This  
15 produces a roughly parallel "beam" of sound representative of the input signal (101), which has a wave front F parallel to the array (105). The radiation in the direction of the beam (perpendicular to the wave front) is significantly more intense than in other directions, though in general there will be "side lobes" too. The assumption is that the array (105) has a physical extent which is one or several wavelengths at the sound  
20 frequencies of interest. This fact means that the side lobes can generally be attenuated or moved if necessary by adjustment of the ACMs or ADFs.

The mode of operation may generally be thought of as one in which the array (105) mimics a very large traditional loudspeaker. All of the individual transducers (104) of the array (105) are operated in phase to produce a symmetrical beam with a  
25 principle direction perpendicular to the plane of the array. The sound field obtained will be very similar to that which would be obtained if a single large loudspeaker having a diameter D was used.

#### Second Sound Field

30

The first sound field might be thought of as a specific example of the more general second sound field.

Here, the delay applied to each replica by the signal delay means (1508) or adjustable digital filter (1512) is made to vary such that the delay increases systematically amongst the transducers (104) in some chosen direction across the surface of the array. This is illustrated in Figure 7B. The delays applied to the various signals before they are routed to their respective output transducer (104) may be visualised in Figure 7B by the dotted lines extending behind the transducer. A longer dotted line represents a longer delay time. In general, the relationship between the dotted lines and the actual delay time will be  $d_n = t_n * c$  where  $d_n$  represents the length of the dotted line,  $t$  represents the amount of delay applied to the respective signal and  $c$  represents the speed of sound in air.

As can be seen from Figure 7B, the delays applied to the output transducers increase linearly as you move from left to right in Figure 7B. Thus, the signal routed to the transducer (104a) has substantially no delay and thus is the first signal to exit the array. The signal routed to the transducer (104b) has a small delay applied so this signal is the second to exit the array. The delays applied to the transducers (104c, 104d, 104e etc) successively increase so that there is a fixed delay between the outputs of adjacent transducers.

Such a series of delays produces a roughly parallel "beam" of sound similar to that produced for the first sound field except that now the beam is angled by an amount dependent on the amount of systematic delay increase that was used. For very small delays ( $t_n \ll T_c$ ,  $n$ ) the beam direction will be very nearly orthogonal to the array (105); for larger delays ( $\max t_n \sim T_c$ ) the beam can be steered to be nearly tangential to the surface.

As already described, sound waves can be directed without focussing by choosing delays such that the same temporal parts of the sound waves (those parts of the sound waves representing the same information) from each transducer together form a front  $F$  travelling in a particular direction.

By reducing the amplitudes of the signals presented by a Distributor to the

SETs located closer to the edges of the array (relative to the amplitudes presented to the SETs closer to the middle of the array), the level of the side lobes (due to the finite array size) in the radiation pattern may be reduced. For example, a Gaussian or raised cosine curve may be used to determine the amplitudes of the signals from each SET. A trade off is achieved between adjusting for the effects of finite array size and the decrease in power due to the reduced amplitude in the outer SETs.

### 10 Third Sound Field

If the signal delay applied by the signal delay means (1508) and/or the adaptive digital filter (1512) is chosen such that the sum of the delay plus the sound travel time from that SET (104) to a chosen point in space in front of the DPAA are for all of the SETs the same value - ie. so that sound waves arrive from each of the output transducers at the chosen point as in-phase sounds - then the DPAA may be caused to focus sound at that point, P. This is illustrated in Figure 7C.

As can be seen from Figure 7C, the delays applied at each of the output transducers (104a through 104h) again increase, although this time not linearly. This causes a curved wave front F which converges on the focus point such that the sound intensity at and around the focus point (in a region of dimensions roughly equal to a wavelength of each of the spectral components of the sound) is considerably higher than at other points nearby.

The calculations needed to obtain sound wave focussing can be generalised as follows:-

$$\text{focal point position vector, } \mathbf{f} = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$



$$\text{nth transducer position, } \mathbf{p}_n = \begin{bmatrix} p_{nx} \\ p_{ny} \\ p_{nz} \end{bmatrix}$$

$$\text{transit time for nth transducer, } t_n = \frac{1}{c} \sqrt{(\mathbf{f} - \mathbf{p}_n)^T (\mathbf{f} - \mathbf{p}_n)}$$

$$\text{required delay for each transducer, } d_n = k - t_n$$

where  $k$  is a constant offset to ensure that all delays are positive and hence realisable.

5

The position of the focal point may be varied widely almost anywhere in front of the DPAA by suitably choosing the set of delays as previously described.

#### Fourth Sound Field

10

Figure 7D shows a fourth sound field wherein yet another rationale is used to determine the delays applied to the signals routed to each output transducer. In this embodiment, Huygens wavelet theorem is invoked to simulate a sound field which has an apparent origin O. This is achieved by setting the signal delay created by the signal delay means (1508) or the adaptive digital filter (1512) to be equal to the sound travel time from a point in space behind the array to the respective output transducer. These delays are illustrated by the dotted lines in Figure 7D.

It will be seen from Figure 7D that those output transducers located closest to the simulated origin position output a signal before those transducers located further away from the origin position. The interference pattern set up by the waves emitted from each of the transducers creates a sound field which, to listeners in the near field in front of the array, appears to originate at the simulated origin.

Hemispherical wave fronts are shown in Figure 7D. These sum to create the wave front F which has a curvature and direction of movement the same as a wave

front would have if it had originated at the simulated origin. Thus, a true sound field is obtained. The equation for calculating the delays is now:-

$$d_n = t_n - j$$

where  $t_n$  is defined as in the third embodiment and  $j$  is an arbitrary offset.

5

It can be seen, therefore, that the general method utilised involves using the replicator (1504) to obtain N replica signals, one for each of the N output transducers. Each of these replicas are then delayed (perhaps by filtering) by respective delays which are selected in accordance with both the position of the  
10 respective output transducer in the array and the effect to be achieved. The delayed signals are then routed to the respective output transducers to create the appropriate sound field.

The distributor (102) preferably comprises separate replicating and delaying means so that signals may be replicated and delays may be applied to each replica.  
15 However, other configurations are included in the present invention, for example, an input buffer with N taps may be used, the position of the tap determining the amount of delay.

The system described is a linear one and so it is possible to combine any of the above four effects by simply adding together the required delayed signals for a  
20 particular output transducer. Similarly, the linear nature of the system means that several inputs may each be separately and distinctly focussed or directed in the manner described above, giving rise to controllable and potentially widely separated regions where distinct sound fields (representative of the signals at the different inputs) may be established remote from the DPAA proper. For example, a first  
25 signal can be made to appear to originate some distance behind the DPAA and a second signal can be focussed on a position some distance in front of the DPAA.

#### First Aspect of the Invention

The first aspect of the invention relates to the use of a DPAA in a multichannel system. As already described, different channels may be directed in different directions using the same array to provide special effects. Figure 8 schematically shows this in plan view the array (3801) is used to direct a first beam of sound (B1) substantially straight ahead towards a listener (X). This can be either focussed or not as shown in Figures 7A or 7B. A second beam (B2) is directed at a slight angle, so that the beam passes by the listener (X) and undergoes multiple reflections from the walls (3802), eventually reaching the listener again. A third beam (B3) is directed at a stronger angle so that it bounces once off the side wall and reaches the listener. A typical application for such a system is a home cinema system in which Beam B1 represents a centre sound channel, beam B2 represents a right surround (right rear speaker in conventional systems) sound channel and beam B3 represents a left sound channel. Further beams for the right channel and left surround channel may also be present but are omitted from Figure 8 for clarity. As is evident, the beams travel different distances before reaching the user. For example, the centre beam may travel 4.8m, the left and right channels may travel 7.8m and the surround channels travel 12.4m. To account for this, an extra delay can be applied to the channels which travel the shortest distance so that each channel reaches the user substantially simultaneously.

Apparatus for achieving this is shown in Figure 9. Three channels (3901,3902,3903) are input to respective delay means (3904). The delay means (3904) delay each channel in time by an amount determined by a delay controller (3909). The delayed channels then pass to distributors (3905), adders (3906), amplifiers (3907) and output transducers (3908). The distributors (3905) replicate and delay the replicas so as to direct the channels in different directions as shown in Figure 8. The delay controller (3909) chooses delays based on the expected distance sound waves of that channel will travel before reaching the user. Using the above example, the surround channel travels the furthest and so is not delayed at all. The left channel is delayed by 13.5 ms so it arrives at the same time as the surround channel and the centre channel is delayed by 22.4 ms so that it arrives at the same

time as the surround channel and the left channel. This ensures that all channels reach the listener at the same time. If the direction of the channels is changed, the delay controller (3909) can take account of this and adjust the delays accordingly. In Figure 9, the delay means (3904) are shown before the distributors. However, they  
5 may beneficially be incorporated into the distributors so that the delay controller (3909) inputs a signal to each distributor and this delay is applied to all replicated signals output by that distributor. Further, in another practical alternative, there can be used a single delay controller (3909) which chooses the resultant delay for each channel replica and thus sends delay data to each distributor, without the need for  
10 separate delaying elements (3904).

#### Second Aspect of the Invention

In the above described first aspect, the delays in the sound reaching the user  
15 can be considerable and become more noticeable as they increase in magnitude. For audio-video applications, this can cause the pictures to lead the sound giving an unpleasant effect. This problem can be solved by use of the apparatus shown in Figure 10. Corresponding audio and video signals are supplied from a source such as a DVD player (4001). These signals are read out simultaneously and have a temporal  
20 correspondence. A channel splitter (4004) is used to obtain each channel of audio from the audio signal and each channel is applied to the apparatus shown in Figure 9. The audio delay controller (3909) is connected to a video delay means (4005) so that the video signal can be delayed by an appropriate amount so that sound and pictures reach the user at the same time. The output from the video delay means is then  
25 output to screen means (4006). The video delay applied is generally calculated with reference to the greatest distance travelled by a sound beam, ie the surround channel in Figure 8. The video delay in this case would be set to be equal to the travel time of beam B2, which is not delayed by audio delay means (3904). It is usually desirable to delay the video signal by an integer number of frames, meaning that the  
30 video delay values are only approximately equal to the calculated value. Even the

surround channels may undergo some delay due to any processing (eg filtering) they undergo. Thus, a further component may be added to the video delay value to account for this processing delay. Further, it is often simpler to delay the video signal until the sound that reaches the listener on a direct path (eg Beam B1 in Figure 5 8) leaves the speaker. The resulting error is generally small, and listeners are accustomed to it from current AV systems. Claims 11 and 16 are intended to cover the system whereby this and approximations due to integer video frames are used, by virtue of the phrase "at substantially the time".

As a refinement, the video delay means can be connected (see dotted line in 10 Figure 10) as well to each distributor (3905) so that appropriate account can be taken of any delays applied for reasons of beam directivity too. As a further refinement, the video-processing circuitry can be used to provide an on-screen display of the user interface of the sound system. In a more general software embodiment, each component of audio delay would be calculated by a microprocessor as part of a 15 program and a complete delay value would be calculated for each replica. These values would then be used to calculate the appropriate video delay.

### Third Aspect of the Invention

20 When multiple channels are used, it can be beneficial to apply a different window function to each channel. The window function reduces the effects of "side lobes" at the expense of power. The type of window function used is chosen dependent on the qualities required of the resultant beam. Thus, if beam directivity is important, a window function as is shown in Figure 11A should be used. If less 25 directivity is required, a more gentle function as shown in Figure 11D can be used.

An apparatus for achieving this is shown in Figure 12. This apparatus is substantially the same as that shown in Figure 9, except the extra delay means (3904) are omitted. Such extra delay means can be combined with this aspect of the invention however. An extra component (4101) is positioned after the distributors in 30 Figure 12. This component applies the windowing function. This component can

beneficially be combined with the distributors but is shown separately for clarity. The windowing means (4101) applies a window function to the set of replicas for a channel. Thus, the system can be configured so that different window functions are chosen for each channel.

5        This system has a further advantage. Channels having a high bass content are generally required to have a high level and directivity is not so important. Thus, the window function can be altered for such channels to meet these needs. An example is shown in Figures 11A-D. Figure 11A shows a typical window function.

Transducers near the outside of array (4102) have a lower output level than those in  
10   the centre to reduce side lobes and improve directivity. If the volume is turned up, all output levels increase and some transducers in the centre of the array may saturate (see Figure 11B), having reached full scale deflection (FSD). To avoid this, the shape of the window function can be changed instead of merely amplifying the output of each transducer. This is shown in Figures 11C and 11D. As the volume is  
15   increased, the outer transducers play a greater role in contributing to the overall sound. Although this increases the side lobes, it also increases the power output giving a louder sound, without any clipping (saturation).

The above technique is most important for the higher frequency components. Thus, the present aspect can be combined with the fourth aspect (see later)  
20   advantageously. For lower frequencies, where directivity is less attainable and less important a flat ("Boxcar") window function may be used to achieve maximum power output. Also, the changing of the window function to account for increased volume as shown in figure 11D is not essential and saturation as shown in Figure 11B may not in practice appreciably deteriorate quality since the windows still falls  
25   off to zero avoiding a discontinuity at the edges and a discontinuity in level is more damaging than a discontinuity in gradient, as shown in Figure 11B.

#### Fourth Aspect of the Invention

30        The directivity achievable with the array is a function of the frequency of the

signal to be directed and the size of the array. To direct a low frequency signal, a larger array is necessary than to direct a high frequency signal with the same resolution. Furthermore, low frequencies generally require more power than high frequencies. Thus, it is advantageous to split an input signal into two or more  
5 frequency bands and deal with these frequency bands separately in terms of the directivity which is achieved using the DPAA apparatus.

Figure 13 illustrates the general apparatus for selectively beaming distinct frequency bands.

Input signal 101 is connected to a signal splitter/combiner (2903) and hence  
10 to a low-pass-filter (2901) and a high-pass-filter (2902) in parallel channels. Low-pass-filter (2901) is connected to a Distributor (2904) which connects to all the adders (2905) which are in turn connected to the N transducers (104) of the DPAA (105).

High-pass-filter (2902) connects to a device (102) which is the same as  
15 device (102) in Figure 1 (and which in general contains within it N variable-amplitude and variable-time delay elements), which in turn connects to the other ports of the adders (2905).

The system may be used to overcome the effect of far-field cancellation of the low frequencies, due to the array size being small compared to a wavelength at those  
20 lower frequencies. The system therefore allows different frequencies to be treated differently in terms of shaping the sound field. The lower frequencies pass between the source/detector and the transducers (2904) all with the same time-delay (nominally zero) and amplitude, whereas the higher frequencies are appropriately time-delayed and amplitude-controlled for each of the N transducers independently.  
25 This allows anti-beaming or nulling of the higher frequencies without global far-field nulling of the low frequencies.

It is to be noted that the method according to the fourth aspect of the invention can be carried out using the adjustable digital filters (512). Such filters allow different delays to be accorded to different frequencies by simply choosing  
30 appropriate values for the filter coefficients. In this case, it is not necessary to

separately split up the frequency bands and apply different delays to the replicas derived from each frequency band. An appropriate effect can be achieved simply by filtering the various replicas of the single input signal.

Figure 14 shows another embodiment of this aspect in which different sets of  
5 output transducers of the array are used to transmit different frequency bands of the input signal (101). As in Figure 13, the input signal (101) is split into a high frequency band by a high pass filter (3402) and a low frequency band by a low pass filter (3405). The low frequency signal is routed to a first set of transducers (3404) and the high frequency band is routed to a second set of transducers (3405). The first  
10 set of transducers (3404) span a larger physical extent of the array than the high frequency transducers (3405) do. Typically, the extent (that is, the magnitude of a characteristic dimension) spanned by a set of transducers is roughly proportional to the shortest wavelength to be transmitted. This gives roughly equal directivity for both (or all if more than two) frequency bands.

15 Figures 15 shows a further embodiment of this aspect in which some output transducers are shared between bands. Again, the signal is split into low and high frequency components by lowpass filter (3501) and a high pass filter (3502). The low frequency distributor (3503) routes appropriately delayed replicas of the low frequency component of the input signal to a first set of the output transducers  
20 (3505). In this example, this first set comprises all the transducers in the array. The high frequency distributor routes the high frequency component of the input signal to a second set of output transducers (3506). These transducers are a subset of the whole array and, as shown in the Figure, may be the same ones as are used to output the low frequency component. In this case, adders (3504) are required to add the low  
25 frequency and high frequency signals prior to output. Thus, in this embodiment, more transducers are used to output the low frequency component and thus more power can be achieved where it is needed at the low frequencies. To further improve the power output at low frequencies, the outer transducers (which output solely low frequencies) can be larger and more powerful.

30 This method has the advantage that the directivity achieved is the same across



all frequencies and a minimum of transducers are used for the high frequencies, resulting in decreased complexity and cost. This is especially the case when a set-up such as is shown in Figure 14 is used, with low-frequency specific transducers around the outside of the array and high frequency transducers near the centre. This  
5 has the further advantage that cheaper limited range transducers may be used rather than full-range transducers.

Figure 16 shows schematically a front view of an array of transducers, each symbol representing a transducer (note the symbols are not intended to relate in any way to the shape of the transducers used). When the method of Figure 14 is used, the  
10 square symbols represent transducers which are used to output low frequency components. The circle symbols represent transducers which output mid-range components and the triangle symbols represent transducers which output high frequency components.

When the method of Figure 15 is used, the triangle symbols represent  
15 transducers which output components of all three frequency ranges. The circle symbols represent transducers which output only mid-range and low frequency signals and the square symbols represent transducers which output only low frequencies.

This aspect of the invention is fully compatible with the above-described  
20 third aspect since windowing functions can be used, with the calculation taking place after the distributors (3403, 3503, 3507). When dedicated transducers are used (as in Figure 14), the "hole" in the low frequency window function caused by the presence of a centre array of high frequency transducers is not usually detrimental to performance, especially if the hole is sufficiently small with respect to the shortest  
25 wavelengths reproduced by the low frequency channel.

It is evident from Figure 16 that less transducers are used for the high frequencies than for the low frequencies and that the spacing between adjacent transducers is constant. However, the maximum acceptable transducer spacing is a function of wavelength so that to avoid sidelobes at high frequencies requires more  
30 tightly packed (eg every  $\lambda/2$ ) transducers. This makes it expensive in terms of

transducers and drive electronics to cover an area large enough to direct low frequencies on the one hand but with tightly spaced transducers to direct high frequencies on the other hand. To solve this problem, an array as shown in Figure 17 is provided. This array has a higher than average density of output transducers  
5 located near the centre portion. Thus, more closely packed transducers can be used to output the high frequencies without increasing the extent of the array and thus the directivity of the beam. The large low frequency area is covered by less closely packed transducers whereas the central high frequency area has a more tightly packed area, optimising cost and performance at all frequencies. In Figure 17, the squares  
10 merely show the presence of a transducer and not the shape or the type of signal output, as in Figure 16.

#### Fifth Aspect of the Invention

15 Figure 18 shows a transducer having a length  $L$  longer than its width  $W$ . This transducer can advantageously be used in an array of like transducers as shown in Figure 19. Here, the transducers 3701 are positioned next to one another in a line such that the line extends in the perpendicular direction to the longest side of each transducer. This arrangement provides a sound field which can be directed well in  
20 the horizontal plane and which, thanks to the elongated shape of each transducer, has most of its energy in the horizontal plane. There is very little sound energy directed to other planes resulting in good efficiency of operation. Thus, the fifth aspect provides a 1-dimensional array made of elongated transducers which gives tight directivity in one direction (thanks to the elongated shape) and controllable  
25 directivity in the other (thanks to the array nature). The aspect ratio of each transducer is preferably at least 2:1, more preferably 3:1 and more preferably still 5:1. The elongate nature of each transducer causes the effect of sound being concentrated in a plane whereas the array of transducers in a line gives good directivity within the plane. This array may be used as the array in any of the other  
30 aspects of the invention.

Sixth Aspect of the Invention

The sixth aspect of the invention relates to the use of a DPAA system to create a surround sound or stereo effect using only a single sound emitting apparatus  
5 similar to the apparatus described above. Particularly, the sixth aspect of the invention relates to directing different channels of sound in different directions so that the soundwaves impinge on a reflective or resonant surface and are re-transmitted thereby.

This sixth aspect of the invention addresses the problem that where the  
10 DPAA is operated outdoors (or any other place having substantially anechoic conditions) an observer needs to move close to those regions in which sound has been focussed in order to easily perceive the separate sound fields. It is otherwise difficult for the observer to locate the separate sound fields which have been created.

If an acoustic reflecting surface, or alternatively an acoustically resonant body  
15 which re-radiates absorbed incident sound energy, is placed in the path of a sound beam, it re-radiates the sound, and so effectively becomes a new sound source, remote from the DPAA, and located at a region determined by the focussing used (if any). If a plane reflector is used then the reflected sound is predominantly directed in a specific direction; if a diffuse reflector is present then the sound is re-radiated more  
20 or less in all directions away from the reflector on the same side of the reflector as the sound is incident from the DPAA. Thus, if a number of distinct sound signals representative of distinct input signals are directed towards distinct regions by the DPAA in the manner described, and within each region is placed such a reflector or resonator so as to redirect the sound from each region, then a true multiple separated-  
25 source sound radiator system may be constructed using a single DPAA of the design described herein.

Figure 20 illustrates the use of a single DPAA and multiple reflecting or resonating surfaces (2102) to present multiple sources to listeners (2103). As it does not rely on psychoacoustic cues, the surround sound effect is audible throughout the  
30 listening area.

The sound beams may be unfocussed, as described above with reference to Figures 7A or 7B, or focussed, as described above with reference to Figure 7C. The focus position can be chosen to be either in front of, at, or behind the respective reflector/resonator to achieve the desired effect. Figure 21 schematically shows the effect achieved when a sound beam is focussed in front of and behind a reflector respectively. The DPAA (3301) is operable to direct sound towards the reflectors (3302 & 3303) set up in a room (3304).

In the case when a sound beam is focussed in front of a reflector (3302) at a point F1 (See Figure 21), the beam narrows at the focus point and spreads out thereafter. The beam continues to spread after reflection from reflector and a listener at position P1 will hear the sound. Due to the reflection, the user will perceive the sound as emanating from the ghost focal point F1'. Thus the listener at P1 will perceive the sound as emanating from outside the room (3304). Further, the beam obtained is quite broad so that a large proportion of listeners in the bottom half of the room (3304) will hear the sound.

In the case when a sound beam is focussed behind a reflector (3303) at a point F2 (See Figure 21), the beam is reflected before it has fully narrowed to the focus point. After reflection, the beam spreads out and a listener at position P2 will be able hear the sound. Due to the reflection, the user will perceive the sound as emanating from the reflected focal point F2' in front of the reflector. Thus the listener at P1 will perceive the sound as emanating from close by. Further, the beam obtained is quite narrow so that it is possible to direct sound to a smaller proportion of the listeners in the room. Thus, it can be advantageous for the above reasons to focus the beams at positions other than the reflector/resonator.

Where the DPAA is operated in the manner previously described with multiple separated beams - ie. with sound signals representative of distinct input signals directed to distinct and separated regions - in non-anechoic conditions (such as in a normal room environment) wherein there are multiple hard and/or predominantly sound reflecting boundary surfaces, and in particular where those regions are directed at one or more of the reflecting boundary surfaces, then using

only his normal directional sound perceptions an observer is easily able to perceive the separate sound fields, and simultaneously locate each of them in space at their respective separate focal regions (if there is one), due to the reflected sounds (from the boundaries) reaching the observer from those regions.

- 5           It is important to emphasise that in such a case the observer perceives real separated sound fields which in no way rely on the DPAA introducing artificial psycho-acoustic elements into the sound signals. Thus, the position of the observer is relatively unimportant for true sound location, so long as he is sufficiently far from the near-field radiation of the DPAA. In this manner, multi-channel "surround-
- 10 sound" can be achieved with only one physical loudspeaker (the DPAA), making use of the natural boundaries found in most real environments.

- Where similar effects are to be produced in an environment lacking appropriate natural reflecting boundaries, similar separated multi-source sound fields can be achieved by the suitable placement of artificial reflecting or resonating
- 15 surfaces where it is desired that a sound source should seem to originate, and then directing beams at those surfaces. For example, in a large concert hall or outside environment optically-transparent plastic or glass panels could be placed and used as sound reflectors with little visual impact. Where wide dispersion of the sound from those regions is desired, a sound scattering reflector or broadband resonator could be
- 20 introduced instead (this would be more difficult but not impossible to make optically transparent).

A spherical reflector can be used to achieve diffuse reflection over a wide angle. To further enhance the diffuse reflection effect, the surfaces should have a roughness on the scale of the wavelength of sound frequency it is desired to diffuse.

- 25           The great advantage of this aspect of the present invention is that all of the above may be achieved with a single DPAA apparatus, the output signals for each transducer being built up from summations of delayed replicas of input signals. Thus, much wiring and apparatus traditionally associated with surround sound systems is dispensed with.

Seventh Aspect of the Invention

The seventh aspect of the invention addresses the problem that a user of the DPAA system may not always be easily able to locate where sound of a particular channel is being directed or focussed at any particular time. Conversely, the user may want to direct or focus sound at a particular position in space which requires a complex calculation as to the correct delays to apply etc. This problem is alleviated by providing a video camera means which can be caused to point in a particular direction. Means connected to the video camera can then be used to calculate which direction the camera is pointing in and adjust the delays accordingly.

Advantageously, the camera is under the direct control of the operator (for example on a tripod or using a joystick) and the DPAA controller is arranged to cause sound channel directing to occur wherever the operator causes the camera to point. This provides a very easy to set up system which does not rely on creating mathematical models of the room or other complex calculations.

Advantageously, means may be provided to detect where in the room the camera is focussed. Then, the sound beams can be focussed on the same spot. This makes setting up a system very simple since markers can be placed in a room where sound is desired to be focussed and then a camera lens can be focussed on these markers by an operator looking at a television monitor. The system can then automatically set up the software to calculate the correct delays for focussing sound to that spot. Alternatively, reference points in the room can be identified to select sound focussing. For example, a simple model of the room can be pre-programmed so that an operator can select objects in the field of view of the camera so determine the focussing distance. In both the case when the camera focus distance is used and when a room model is used, it is advantageous to employ a coordinate transform from camera (pan, tilt, distance) or room (x,y,z) to speaker (rotation, elevation, distance), where the two coordinate systems have different origins.

In the reverse mode of operation, the camera may be steered automatically by the DPAA electronics such that it points toward the direction in which a beam is

currently being steered, with an automatic focussing on the point where sound focussing occurs, if at all. This provides a great deal of useful set-up feedback information to the operator.

Means to select which channel settings are controlled by the camera position  
5 should also be provided and these may all be controlled from the handset.

Figure 22 illustrates in side view the use of a video camera (3602) positioned on a DPAA (3601) to point at the same point in which sound is focussed. The camera can be steerable using a servo motor (3603). Alternatively, the camera can be mounted on a separate tripod or be hand held or be part of an extant CCTV system.

10 For CCTV applications, where a plurality of cameras are used to cover an area, a single array can be used to direct sound to any position in the area which one of the cameras is pointing at. Thus, an operator can direct sound (such as voice commands or instructions) to a specific point in the area/room by selecting a camera pointing at that point and speaking into a microphone.

15

#### Further Preferable Features

There may be provided means to adjust the radiation pattern and focussing points of signals related to each input, in response to the value of the programme  
20 digital signals at those inputs - such an approach may be used to exaggerate stereo signals and surround-sound effects, by moving the focussing point of those signals momentarily outwards when there is a loud sound to be reproduced from that input only. Thus, the steering can be achieved in accordance with the actual input signal itself.

25 In general, when the focus points are moved, it is necessary to change the delays applied to each replica which involves duplicating or skipping samples as appropriate. This is preferably done gradually so as to avoid any audible clicks which may occur if a large number of samples are skipped at once for example.

Practical applications of this invention's technology include the following:  
30 for home entertainment, the ability to project multiple real sources of sound

to different positions in a listening room allows the reproduction of multi-channel surround sound without the clutter, complexity and wiring problems of multiple separated wired loudspeakers;

for public address and concert sound systems, the ability to tailor the  
5 radiation pattern of the DPAA in three dimensions, and with multiple simultaneous beams allows:

much faster set-up as the physical orientation of the DPAA is not very critical and need not be repeatedly adjusted;

smaller loudspeaker inventory as one type of speaker (a DPAA) can achieve a  
10 wide variety of radiation patterns which would typically each require dedicated speakers with appropriate horns;

better intelligibility, as it is possible to reduce the sound energy reaching reflecting surfaces, hence reducing dominant echoes, simply by the adjustment of filter and delay coefficients; and

15 better control of unwanted acoustic feedback as the DPAA radiation pattern can be designed to reduce the energy reaching live microphones connected to the DPAA input;

for crowd-control and military activities, the ability to generate a very intense sound field in a distant region, which field is easily and quickly repositionable, by  
20 focussing and steering of the DPAA beams (without having physically to move bulky loudspeakers and/or horns) and which is easily directed onto the target by means of tracking light sources, and provides a powerful acoustic weapon which is nonetheless non-invasive; if a large array is used, or a group of coordinated separate DPAA panels possibly widely spaced, then the sound field can be made much more intense  
25 in the focal region than near the DPAA SETs (even at the lower end of the Audio Band if the overall array dimensions are sufficiently large).

Any of the previously described aspects may be combined together in a practical device to provide the stated advantages.



Preferred Embodiment of the First Aspect of the Invention

There now follows a description of a preferred embodiment of the first aspect of the present invention, which, as will become apparent, utilises also the techniques  
5 of the other above-described aspects.

Referring to Figure 23, a digital sound projector 10 comprises an array of transducers or loudspeakers 11 that is controlled such that audio input signals are emitted as a beam of sound 12-1, 12-2 that can be directed into an - within limits - arbitrary direction within the half-space in front of the array. By making use of  
10 carefully chosen reflection paths, a listener 13 will perceive a sound beam emitted by the array as if originating from the location of its last reflection.

In Figure 23, two sound beams 12-1 and 12-2 are shown. The first beam 12-1 is directed onto a side-wall 161 that may be part of a room and reflected directly onto the listener 13. The listener perceives this beam as originating from reflection spot  
15 17, thus from the right. The second beam 12-2, indicated by dashed lines, undergoes two reflections before reaching the listener 13. However, as the last reflection happens in a rear corner, the listener will perceive the sound as if emitted from a source behind him or her.

Whilst there are many uses to which a digital sound projector could be put, it  
20 is particularly advantageous in replacing conventional surround-sound systems employing several separate loudspeakers placed at different locations around a listener's position. The digital sound projector, by generating beams for each channel of the surround-sound audio signal, and steering the beams into the appropriate directions, creates a true surround-sound at the listener position without further  
25 loudspeakers or additional wiring.

In Figures 24 to 26, there are shown components of a digital sound projector system in form of block diagrams. At the input, common-format audio source material in Pulse Code Modulated (PCM) form is received from devices such as compact disks (CDs), digital video disks (DVDs) etc. by the digital sound projector  
30 as either an optical or coaxial digital data stream in the S/PDIF format. But other

input digital data formats can be also used. This input data may contain either a simple two channel stereo pair, or a compressed and encoded multi-channel soundtrack such as Dolby Digital™ 5.1 or DTS™, or multiple discrete digital channels of audio information.

- 5           Encoded and/or compressed multi-channel inputs are first decoded and/or decompressed in a decoder using the devices and licensed firmware available for standard audio and video formats. An analogue to digital converter (not shown) is also incorporated to allow connection (AUX) to analogue input sources which are immediately converted to a suitably sampled digital format. The resultant output
- 10           comprises typically three, four or more pairs of channels. In the field of surround-sound, these channels are often referred to left, right, centre, surround (rear) left and surround (rear) right channels. Other channel may be present in the signal such as the low frequency effect channel (LFE).

- These channels or channel-pairs are each fed into a two-channel sample-rate-
- 15           converter [SRC] (alternatively each channel can be passed through a single channel SRC) for re-synchronisation and re-sampling to an internal (or optionally, external) standard sample-rate clock [SSC] (typically about 48.8KHz or 97.6KHz) and bit-length (typically 24 bit), allowing the internal system clocks to be independent of the source data-clock. This sample rate conversion eliminates problems due to clock
- 20           speed inaccuracy, clock drift, and clock incompatibility. Specifically, if the final power-output stages of the digital sound projector are to be digital pulse-width-modulation [PWM] switched types for high efficiency, it is desirable to have a complete synchronisation between the PWM-clock and the digital data-clock feeding the PWM modulators. The SRCs provide this synchronisation, as well as isolation
- 25           from the vagaries of any external data clocks.

          Finally, where two or more of the digital input channels have different data-clocks (perhaps because they come from separate digital microphone systems e.g.), then again the SRCs ensure that internally all disparate signals are synchronised.

- The outputs of the SRCs are converted to 8 channels of 24bit words at an
- 30           internally generated sample rate of 48.8KHz.

One or more (typically two or three) digital signal processor [DSP] units are used to process the data. These may be e.g. Texas Instruments TMS320C6701 DSPs running at 133MHz, and the DSPs either perform the majority of calculations in floating-point format for ease of coding, or in fixed-point format for maximum processing speed. Alternatively, especially where fixed-point calculations are being performed, the digital signal processing can be carried out in one or more Field Programmable Gate Array (FPGA) units. A further alternative is a mixture of DSPs and FPGAs. Some or all of the signal processing may alternatively be implemented with customised silicon in the form of an Application Specific Integrated Circuit (ASIC).

A DSP stage performs filtering of the digital audio data input signals for enhanced frequency response equalisation to compensate for the irregularities in the frequency response (i.e. transfer function) of the acoustic output-transducers used in the final stage of the digital sound projector.

The number of separately processed channels may optionally, at this stage (preferably) or possibly at an earlier or later stage of processing, be reduced by combining additively the (one or more) low-frequency-effects [LFE] channel with one or more of the other channels, for example the centre channel, in order to minimise the processing beyond this stage. However, if a separate sub-woofer is to be used with the system or if processing power is not an issue, then the more discrete channels may be maintained throughout the processing chain.

The DSP stage also performs anti-alias and tone control filtering on all eight channels, and a eight-times over-sampling and interpolation to an overall eight-times oversampled data rate, creating 8 channels of 24-bit word output samples at 390 KHz. Signal limiting and digital volume-control is performed in this DSP too.

An ARM microprocessor generates timing delay data for each and every transducer, from real-time beam-steering settings sent by the user to the digital sound projector via infrared remote control. Given that the digital sound projector is able to independently steer each of the output channels (one steered output channel for each input channel, typically 4 to 6), there are a large number of separate delay

computations to be performed; this number is equal to the number of output channels times the number of transducers. As the digital sound projector is also able to dynamically steer each beam in real-time, then the computations also need to be performed quickly. Once computed, the delay requirements are distributed to the  
5 FPGAs (where the delays are actually applied to each of the streams of digital data samples) over the same parallel bus as the digital data samples themselves.

The ARM core also handles all system initialisation and external communications.

The signal stream enters Xilinx field programmable gate array logic that  
10 control high-speed static buffer RAM devices to produce the required delays applied to the digital audio data samples of each of the eight channels, with a discretely delayed version of each channel being produced for each and every one of the output transducers (256 in this implementation).

Apodisation, or array aperture windowing (i.e. graded weighting factors are  
15 applied to the signals for each transducer, as a function of each transducer's distance from the centre of the array, to control beam shape) is applied separately in the FPGA to each channel's delayed signal versions. Applying apodisation here allows different output sound beams to have differently tailored beam-shapes. These separately delayed and separately windowed digital sample streams, one for each of 8  
20 channels and for each of 256 transducers making  $8 \times 256 = 2048$  delayed versions in total, are then summed in the FPGA for each transducer to create an individual 390kHz 24-bit signal for each of the 256 transducer elements. The apodisation or array aperture windowing, may optionally be performed after the summing stage for all of the channels at once (instead of for each channel separately, prior to the  
25 summing stage) for simplicity, but in this case each sound beam output from the digital sound projector will have the same window function which may not be optimal.

The two hundred and fifty-six signals at 24-bit and 390kHz are then each passed through a quantizing/noise shaping circuit also in the FPGA to reduce the data  
30 sample word lengths to 8 bits at 390kHz, whilst maintaining a high signal-to-noise-

ratio [SNR] within the audible band (i.e. the signal frequency band from ~20Hz to ~20KHz).

A useful implementation practice is to make the SSC be an exact rational number fraction of the DSP master-processing-clock speed, e.g.  $100\text{MHz} / 256 =$   
5  $390,625\text{ Hz}$  which locks sample data rates throughout the system to the processing clocks. It is advantageous to make the digital PWM timing clock frequency also an exact rational number fraction of the DSP master-processing-clock speed. It is specifically advantageous to make the PWM clock frequency an exact integer multiple of the internal digital audio sample data rate, e.g. 512 times the sample rate  
10 for 9-bit PWM (because  $2^9 = 512$ ). The reduction of the digital data word-length to 8, while simultaneously increasing the sample-rate is useful for several reasons:

i) The increased sample-rate allows finer resolution of data-word delays; e.g. at 48KHz data-rate, the smallest delay increment available is 1 sample period,  
15 or ~21 microseconds, whereas at 195KHz data-rate, the smallest delay increment available is (1 sample period) ~5.1 microseconds. It is important to have sound-path-length compensation resolution (= time-delay resolution times speed-of-sound) fine compared to acoustic output-transducer diameter. In 21 microseconds sound in air at NTP travels approximately 7mm, which is  
20 too coarse a resolution when using transducers as small as 10mm diameter;

ii) It is easier to convert PCM data directly to digital PWM at practical clock-speeds when the word-length is small; e.g. 16-bit words at 48KHz data-rate require a PWM clock speed of  $65536 \times 48\text{KHz} \sim 3.15\text{GHz}$  (largely  
25 impractical), whereas 8-bit words at 195KHz data-rate require a PWM clock speed of  $256 \times 390\text{ KHz} \sim 100\text{MHz}$  (quite practical); and

iii) because of the increased sample rate, there is an increased available signal bandwidth at half the sample rate, so e.g. available signal bandwidth ~96KHz  
30 for a sample rate of ~195KHz; the quantization process (reduction in number

of bits) effectively adds quantization noise to the digital data; by spectrally shaping the noise produced by the quantization process, it can be predominantly moved to the frequencies above the baseband signal (i.e. in our case above  $\sim 20\text{KHz}$ ), in the region between the top of the baseband ( $\sim 20\text{KHz}$  and  $<$  available signal bandwidth  $\sim 96\text{KHz}$ ); the effect is that nearly all of the original signal information is now carried in a digital data stream with very little loss in SNR.

The data stream with reduced sample word width is distributed in 26 serial data streams at 31.25 Mb/s each and additional volume data. Each data stream is assigned to one of 26 driver boards.

The driver circuit boards, as shown in Figure 25, which are preferably physically local to the transducers they drive, provide a pulse-width-modulated class-BD output driver circuit for each of the transducers they control. In the present example, each driver boards is connected to ten transducers, whereby the transducers are directly connected to the output of the class-BD output driver circuits without any intervening low-pass-filter [LPF].

Each PWM generator drives a class-D power switch or output stage which directly drives one transducer, or a series-or-parallel-connected pair of adjacent transducers. The supply voltage to the class-D power switches can be digitally adjusted to control the output power level to the transducers. By controlling this supply voltage over a wide range, e.g. 10:1, the power to the transducer can be controlled over a much wider range, 100:1 for a 10:1 voltage range, or in general  $N^2:1$  for an  $N:1$  voltage range. Thus wide-ranging level control (or "volume" control) can be achieved with no reduction in digital word length, so no degradation of the signal due to further quantization (or loss of resolution) occurs. The supply voltage variation is performed by low-loss switching regulators mounted on the same printed circuit boards (PCBs) as the class-D power switches. There is one switching regulator for each class-D switch to minimise power supply line inter-modulation. To reduce cost, each switching regulator can be used to supply pairs, triplets, quads or

other integer multiples of class-D power switches.

The class-D power switches or output stages, directly drive the acoustic output transducers. In normal class-D power amplifier drives, i.e. the very commonly used so-called "class-AD" amplifiers, it is necessary to place an electronic low-pass-  
5 filter [LPF] (invariably, an analogue electronic LPF) between the class-D power stage and the transducer. This is because the common forms of magnetic transducer (and even more so, piezoelectric transducers) present a low load-impedance to the high-frequency PWM carrier frequencies present at high energy in class-AD amplifier outputs. E.g. a class-AD amplifier with zero baseband input signal  
10 continues to produce at its output, a full amplitude (usually bipolar) 1:1 mark-space-ratio [MSR] output signal at the PWM switching frequency (in the present case this would be at ~50 or 100MHz), which if connected across a nominal 8 Ohm load would dissipate full available power in that load, whilst creating no useful acoustic output signal. The commonly used electronic LPF has a cut off frequency above the  
15 highest wanted signal output frequency (e.g. > 20KHz) but well below the PWM switching frequency ( e.g. ~50MHz), thus effectively blocking the PWM carrier and minimising the wasted power. Such LPFs have to transmit the full signal power to the electrical loads (e.g. the acoustic transducers) with as low power-loss as possible; usually these LPFs use a minimum of two power-inductors and two, or more usually,  
20 three capacitors; the LPFs are bulky and relatively expensive to build. In single-channel (or few-channel) amplifiers, such LPFs can be tolerated on cost grounds, and most importantly, in PWM amplifiers housed separately from their loads (e.g. conventional loudspeakers) which need to be connected by potentially long leads to their loads, such LPFs are in any case necessary for quite different reasons, viz. to  
25 prevent the high-frequency PWM carrier getting into the connecting leads where it will most likely cause unwanted stray electromagnetic radiation [EMI] of relatively high amplitude.

In the digital sound projector, the acoustic transducers are connected directly to the physically adjacent PWM power switches by short leads and all are housed  
30 within the same enclosure, eliminating the problems of EMI. In the digital sound

projector, the PWM generators are of a type known as class-BD; these produce class-BD PWM signals which drive the output power switches and these in turn drive the acoustic output transducers. Class-BD PWM output signals have the property that they return to zero between the full amplitude bipolar pulse outputs, and thus are

5 tristate, not bistate like class-AD signals. Thus, when the digital input signal to a class-BD PWM system is zero, then the class-BD power output state is zero, and not a full-power bipolar 1:1 MSR signal as is produced by class-AD PWM. Thus the class-BD PWM power switch delivers zero power to the load (the acoustic transducer) in this state: no LPF is required as there is no full-power PWM carrier

10 signal to block. Thus in the digital sound projector, by using an array of class-BD PWM amplifiers to drive directly an integral array of transducers, a great saving in cost, and lost power, is achieved, by eliminating the need for an array of power LPFs. Class-BD is rarely used in conventional audio amplifiers, firstly because it is more difficult to make a very high linearity class-BD amplifier, than a similarly linear

15 class-AD amplifier; and secondly because for the reasons stated above an LPF is generally required anyway, for EMI considerations, thus negating the principal benefits of class-BD.

The acoustic output transducers themselves are very effective electroacoustic LPFs and so an absolute minimum of PWM carrier from the class-BD PWM stages is

20 emitted as acoustic energy. Thus in the digital sound projector digital array loudspeaker, the combination of class-BD PWM with direct coupling to in-the-same-box acoustic transducers and without electronic LPFs, is a very effective and cost effective solution to high-efficiency, high-power, multiple transducer driving. Furthermore, since the sound of any one (or more) output channels corresponding to

25 one of the input channels, heard by a listener to the digital sound projector, is a summation of sounds from each and every one of the acoustic output transducers and thus related to a summation of the outputs from each of the power-amplifier stages driving those transducers, non-systematic errors in the outputs of the power switches and transducers will tend to average to zero and be minimally audible. Thus an

30 advantage of the array loudspeaker constructed as described is that it is more



forgiving of the quality of individual components, than in a conventional non-array audio system.

In a particular implementation of the digital sound projector with 254 acoustic output transducers arranged in a triangular array of roughly rectangular extent with one axis of the array vertical (and of extent 7 vertical columns of 20  
5 transducers each separated by 6 column of 19 transducers) and with every second output transducer in each vertical column of transducers connected electrically in series or in parallel with the transducer immediately below it, this results in one hundred and thirty two (132) different versions of each of the channels, the number  
10 of channels being five in this example, i.e., six hundred and sixty channels in total. A transducer diameter small enough to ensure approximately omnidirectional radiation from the transducer up to high audio frequencies (e.g. > 12KHz to 15KHz) is important if the digital sound projector is to be able to steer beams of sound at small angles from the plane of the transducer array. Thus a transducer diameter of between  
15 5mm and 30mm is optimum for whole audio-band coverage. A transducer-to-transducer spacing small compared with the shortest wavelengths of sound to emitted by the digital sound projector is desirable to minimise the generation of "spurious" sidelobes of acoustic radiation (i.e. beams of acoustic energy produced inadvertently and not emitted in the desired direction(s)). Practical considerations on possible  
20 transducer size dictate that transducer spacing in the range 5mm to 45mm is best. A triangular array layout is also best for high-areal-packing density of transducers in the array.

As illustrated by Figure 26, the digital sound projector user-interface produces overlay graphics for on-screen display of setup, status and control  
25 information, on any suitably connected video display, e.g. a plasma screen. To this end the video signal from any connected audio-visual source (e.g. a DVD player) may be looped through the digital sound projector en route to the display screen where the digital sound projector status and command information is then also overlaid on the programme video. If the process delay of the signal processing  
30 operations from end to end of the digital sound projector are sufficiently long, (e.g.

when the length of the compensation filter running on the first two DSPs which depends on the transducer linearity and the equalisation required, is long) then to avoid lip-sync problems, an optional video frame store can be incorporated in the loop-through video path, to re-synchronise the displayed video with the output

5 sound.

CLAIMS

1. A method of creating a sound field comprising a plurality of channels of sound using an array of output transducers, said method comprising:
  - 5 for each channel, selecting a first delay value in respect of each output transducer, said first delay value being chosen in accordance with the position in the array of the respective transducer;  
selecting a second delay value for each channel, said second delay value being chosen in accordance with the expected travelling distance of sound waves of  
10 that channel from said array to a listener;  
obtaining, in respect of each output transducer, a delayed replica of a signal representing each channel, each delayed replica being delayed by a value having a first component comprising said first delay value and a second component comprising said second delay value.
- 15 2. A method according to claim 1 or 2, wherein said second delay is applied to each signal representing said channel before said signal is replicated; each replica then being delayed by the respective first delay value.
- 20 3. A method according to claim 1 or 2, wherein said first delay value is also chosen in accordance with a given direction so that each channel of sound is directed in respective direction.
4. A method according to claim 3, wherein each channel is directed in a  
25 different respective direction.
5. A method according to any one of the preceding claims, wherein said second delay value is chosen such that corresponding parts of all sound channels reach the listener at substantially the same time.

6. Apparatus for creating a sound field comprising:  
a plurality of inputs for a plurality of respective signals representing different sound channels;  
an array of output transducers;  
5 replication means arranged to obtain, in respect of each output transducer, a replica of each respective input signal;  
first delay means arranged to delay each replica of each signal by a respective first delay value chosen in accordance with the position in the array of the respective output transducer;  
10 second delay means arranged to delay each replica of each signal by a second delay value chosen for each channel in accordance with the expected travelling distance of sound waves of that channel from the array to a listener.
7. Apparatus according to claim 6, wherein said second delay means is  
15 arranged to delay said input signals before they are replicated by said replication means.
8. Apparatus according to claim 6 or 7, wherein said first delay value is also chosen in accordance with a given direction so that each channel of sound is  
20 directed in said respective direction.
9. Apparatus according to claim 8, wherein each channel is directed in a different direction.
- 25 10. Apparatus according to any one of claims 6 to 9, wherein said second delay means is arranged to choose said second delay for each channel such that all sound channels reach a listener at substantially the same time.
11. A method of creating a sound field comprising a centre channel and at  
30 least one surround sound channel using an array of output transducers to direct the at

least one surround sound channel in a predetermined direction, said method comprising:

for the at least one surround sound channel, selecting a first delay value in respect of each output transducer, said first delay values being chosen in accordance  
5 with the position in the array of the respective transducer so as to direct the channel in said predetermined direction;

selecting a second delay value for the centre channel, said second delay value being chosen in accordance with the expected travelling distance of sound waves of the channels from the array to the listener;

10 obtaining, in respect of each output transducer, a delayed replica of a signal representing the at least one surround sound channel, each delayed replica being delayed by the first delay value calculated for that output transducer and that channel;

obtaining, in respect of each output transducer, a delayed replica of a signal representing the centre channel, each delayed replica being delayed by said second  
15 delay value;

outputting said delayed replicas using said array of output transducers.

12. A method according to claim 11, further comprising:

for the centre channel, selecting a first delay value in respect of each output  
20 transducer, said first delay values being chosen in accordance with the position in the array of the respective transducer so as to direct the centre channel in a predetermined direction;

and wherein said step of obtaining, in respect of each output transducer, a delayed replica of a signal representing the centre channel further comprises:

25 delaying each replica of the signal representing said centre channel by the first delay value calculated for the respective output transducer and the centre channel.

13. A method according to claim 11, wherein replicas of the signal  
30 representing said centre channel are not delayed by values other than said second

delay value, said second delay values being the same for each replica of the signal.

14. A method according to any one claims 11 to 13, further comprising:  
for the at least one surround sound channel, selecting a second delay value in  
5 respect of each output transducer, said second delay value being chosen in  
accordance with the expected travelling distance of sound waves of the channels  
from the array to the listener;

and wherein said step of obtaining, in respect of each output transducer, a  
delayed replica of a signal representing the at least one surround sound channel  
10 further comprises:

delaying each replica of the signal representing said at least one surround  
sound channel by the second delay value calculated for the respective output  
transducer and the at least one surround sound channel.

15 15. A method according to any one of claims 11 to 14, wherein said  
second delay is applied to each signal representing said centre channel before said  
signal is replicated.

16. A method according to any one of claims 11 to 15, wherein said sound  
20 field comprises two surround sound channels, each surround sound channel being  
directed in a different direction.

17. A method according to any one of claims 11 to 16, wherein said  
second delay value is chosen such that corresponding parts of all sound channels  
25 reach the listener at substantially the same time.

18. A method according to any one of claims 11 to 17, wherein said  
delayed replicas of the signal representing the at least one surround sound channel  
are added to respective delayed replicas of the signal representing the centre channel  
30 before being output by the respective output transducers.

19. A method according to any one of claims 11 to 18, wherein the sound waves of said at least one surround sound channel are bounced off a surface such as a wall before reaching the listener.

5 20. Apparatus for creating a sound field comprising:

means for receiving a plurality of input signals representing at least one surround sound channel and a centre channel;

an array of output transducers;

replication means arranged to obtain, in respect of each output transducer, a  
10 replica of said signal representing said at least one surround sound channel and a replica of said signal representing a centre channel;

first delay means arranged to delay each replica of said signal representing said at least one surround sound channel by a respective first delay value chosen in accordance with the position in the array of the respective transducer so as to direct  
15 the channel in a predetermined direction;

second delay means arranged to delay each replica of said signal representing said centre channel by a second delay value chosen in accordance with the expected travelling distance of sound waves of the channels from the array to a listener.

20 21. Apparatus according to claim 20, wherein said first delay means is also arranged to delay each replica of said signal representing said centre channel by a respective first delay value chosen in accordance with the position in the array of the respective transducer so as to direct the centre channel in a predetermined direction.

25

22. Apparatus according to claim 20 or 21, wherein said second delay means is also arranged to delay each replica of said signal representing said at least one surround sound channel by a respective second delay value chosen in accordance with the expected travelling distance of sound waves of the channels from the array  
30 to the listener.

23. Apparatus according to any one of claims 20 to 22, wherein said second delay means is arranged to delay said input signals before they are replicated by said replication means.

5        24. Apparatus according to any one of claims 20 to 23, wherein said sound field comprises two surround sound channels, and said first delay means is arranged to cause each surround sound channel to be directed in a different direction.

25. Apparatus according to any one of claims 20 to 24, wherein said  
10 second delay means is arranged to choose said second delay for the channels such that all sound channels reach a listener at substantially the same time.

26. Apparatus according to any one of claims 20 to 25, wherein said first delay means and said second delay means are the same physical means.

15

27. A method according to any one of claims 11 to 19 or an apparatus according to any one of claims 20 to 26, wherein said output transducers are directly driven by class-BD PWM amplifiers.

20        28. A method of providing temporal correspondence between pictures and sound in an audio-visual presentation using an array of output transducers to reproduce the sound content comprising a plurality of channels, said method comprising:

25        delaying, in respect of each output transducer, a replica of each signal representing a sound channel by a respective audio delay value;

      delaying a video signal by a video delay value calculated so corresponding video pictures are displayed at substantially the time the temporally corresponding sound channels reach the listener.

30        29. A method according to claim 28, wherein each audio delay value is



calculated in accordance with the position in the array of the respective transducer.

30. A method according to claim 29, wherein each audio delay value is also calculated in accordance with the expected travelling distance of sound waves of  
5 that channel from said array to a listener.

31. A method according to claim 30, wherein each audio delay value is calculated such that temporally corresponding parts of each sound channel reach the listener at substantially the same time.

10

32. A method according to any one of claims 28 to 31, wherein said video delay value is calculated so as to have a component equal to the time taken for the sound channel having the greatest distance to travel between said array and said  
listener to travel between said array and said listener.

15

33. Apparatus to provide temporal correspondence between pictures and a plurality of sound channels in an audio-visual presentation comprising:  
an array of output transducers;  
replication and delay means arranged to obtain, in respect of each output  
20 transducer, a delayed replica of each signal representing a sound channel;  
video delay means arranged to delay a corresponding video signal by a video delay value calculated so corresponding video pictures are displayed at substantially the time the temporally corresponding sound channels reach the listener.

25 34. Apparatus according to claim 33, wherein said replication and delay means is arranged so that each audio delay value is calculated in accordance with the position in the array of the respective transducer.

35. Apparatus according to claim 34, wherein said replication and delay  
30 means is arranged so that each audio delay value is also calculated in accordance

with the expected travelling distance of sound waves of that channel from said array to a listener.

36. Apparatus according to claim 35, wherein said replication and delay  
5 means is arranged so that each audio delay value is calculated such that temporally corresponding parts of each sound channel reach the listener at substantially the same time.

37. Apparatus according to claims 33 to 36, wherein said video delay  
10 means is arranged so that said video delay value is calculated so as to be equal to the time taken for the sound channel having the greatest distance to travel between said array and said listener to travel between said array and said listener.

38. A method of creating a sound field comprising a plurality of channels  
15 of sound using an array of output transducers, said method comprising:

for each channel, obtaining, in respect of each output transducer, a replica of a signal representing said channel so as to obtain a set of replica signals for each channel;

applying a first window function to a first set of replica signals originating  
20 from a first sound channel signal;

applying a second, different, window function to a second set of replica signals originating from a second sound channel signal.

39. A method according to claim 38, wherein applying a window function  
25 comprises:

attenuating or amplifying each replica signal such that replica signals destined for output transducers near the centre of the array are attenuated less or amplified more than replica signals destined for output transducers near the edges of the array, the amount of attenuation or amplification being determined by said window  
30 function.

40. A method according to claim 38 or 39, wherein the window function used is selected in accordance with how the respective sound channel is output by the array.

5 41. A method according to any one of claims 38 to 40, wherein the window function used is selected in accordance with a required beam type for that channel.

42. A method according to any one of claims 38 to 41, wherein the  
10 window function used has a shape alterable as a function of a volume control.

43. Apparatus to create a sound field comprising a plurality of channels of sound, comprising:

an array of output transducers;

15 replication means for providing, in respect of each output transducer, a replica of a signal representing each of said plurality of channels;

windowing means for applying a first window function to a first set of replica signals originating from a first sound channel signal and for applying a second, different, window function to a second set of replica signals originating from a  
20 second channel signal.

44. Apparatus according to claim 43, wherein said windowing means is arranged to attenuate or amplify each replica signal such that replica signals destined for output transducers near the centre of the array are attenuated less or amplified  
25 more than replica signals destined for output transducers near the edges of the array, the amount of attenuation or amplification being determined by said window function.

45. Apparatus according to claim 43 or 44, wherein said windowing  
30 means is provided directly after said replication means.

46. Apparatus according to any one of claims 43 to 45, wherein said windowing means is arranged to select a window function in accordance with a required beam type for that channel.

5 47. Apparatus according to any one of claims 43 to 46, wherein the window function applied to a set of replicas originating from a signal representing a channel is altered in shape in accordance with the volume selected for said channel.

48. A method of creating a sound field using an array of output  
10 transducers, said method comprising:  
dividing an input signal into at least a low frequency component and a high frequency component;  
using output transducers spanning a first portion of the array to output said low frequency component; and  
15 using output transducers spanning a second portion of said array smaller than said first portion to output said high frequency component.

49. A method according to claim 48, wherein said second portion  
comprises a subset of said output transducers located near the centre of the array.  
20

50. A method according to claim 48 or 49, wherein there are 3 or more divided signal frequency components and the portion of the array used for a signal component is determined such that the ratio of the shortest wavelength in said signal component to the portion of array used to output said signal component is  
25 substantially constant for all signal components.

51. A method according to any one of claims 48 to 50, wherein said second portion of the array used for said high frequency component is not used for said low frequency component.

52. A method according to any one of claims 48 to 51, wherein said second portion of the array used for said high frequency component comprises a greater density of output transducers than the array as a whole on average.

5 53. An apparatus arranged to perform the method according to any one of claims 48 to 52.

54. Apparatus for creating a sound field comprising:  
an array of output transducers wherein in a first area of the array the output  
10 transducers are more densely packed than in the remainder of said array.

55. Apparatus according to claim 54, wherein said first area is located substantially at the centre of the array.

15 56. Apparatus according to claim 54 or 55, wherein the output transducers in said first area are less powerful than the output transducers in the remainder of the array.

57. Apparatus according to any one of claims 54 to 56, wherein the output  
20 transducers in said first area are smaller than the output transducers in the remainder of the array.

58. Apparatus according to any one of claims 54 to 57, further comprising means for routing a high frequency component of a signal to said first area of the  
25 array, but not to the remainder of the array.

59. Apparatus according to any one of claims 54 to 58, further comprising means to route a low frequency components of a signal to the remainder of the array.

30 60. An array of output transducers positioned next to each other in a line;

wherein each of said output transducers has a dimension in the direction perpendicular to said line larger than the dimension parallel to said line.

61. An array according to claim 60, wherein each output transducer has an aspect ratio defined as the ratio of the dimension perpendicular to the line to the dimension parallel to the line and said aspect ratio is at least 2:1.

62. An array according to claim 61, wherein said aspect ratio is at least 3:1.

63. An array according to any one of claims 60 to 62, wherein said arrangement is such that sound is concentrated substantially in a plane containing said line and extending perpendicularly away from the sound emitting side of said transducers.

64. A method of causing plural input signals representing respective channels to appear to emanate from respective different positions in space, said method comprising:

providing a sound reflective or resonant surface at each of said positions in

space;

providing an array of output transducers distal from said positions in space;

and

directing, using said array of output transducers, sound waves of each channel towards the respective position in space to cause said sound waves to be re-

transmitted by said reflective or resonant surface, said sound waves being focussed at a position in space in front of, or behind, said reflective or resonant surface;

said step of directing comprising:

obtaining, in respect of each transducer, a delayed replica of each input signal delayed by a respective delay selected in accordance with the position in the array of the respective output transducer and said respective focus position such that the

sound waves of the channel are directed towards the focus position in respect of that channel;

summing, in respect of each transducer, the respective delayed replicas of each input signal to produce an output signal; and

5 routing the output signals to the respective transducers.

65. A method according to claim 64, wherein said step of obtaining, in respect of each output transducer, a delayed replica of the input signal comprises:

replicating said input signal said predetermined number times to obtain a  
10 replica signal in respect of each output transducer;

delaying each replica of said input signal by said respective delay selected in accordance with the position in the array of the respective output transducer and the desired position of focus.

15 66. A method according to claim 64 or claim 65, further comprising:  
calculating, before said delaying step, the respective delays in respect of each input signal replica by:

determining the distance between each output transducer and the focus position in respect of that input signal;

20 deriving respective delay values such that the sound waves from each transducer for a single channel arrive at said focus position in space simultaneously.

67. A method according to any one of claims 64 to 66, wherein at least one of said surfaces is provided by a wall of a room or other permanent structure.

25

68. An apparatus for causing plural input signals representing respective channels to appear to emanate from respective different positions in space, said apparatus comprising:

a sound reflective or resonant surface at each of said positions in space;

30 an array of output transducers distal from said positions in space; and

a controller for directing, using said array of output transducers, sound waves of each channel towards that channel's respective position in space such that said sound waves are re-transmitted by said reflective or resonant surface, said sound waves being focussed at a position in space in front of, or behind, said reflective or  
5 resonant surface;

said controller comprising:

replication and delay means arranged to obtain, in respect of each transducer, a delayed replica of the input signal delayed by a respective delay selected in accordance with the position in the array of the respective output transducer and the  
10 respective focus position such that the sound waves of the channel are directed towards the focus position in respect of that input signal;

adder means arranged to sum, in respect of each transducer, the respective delayed replicas of each input signal to produce an output signal; and

means to route the output signals to the respective transducers such that the  
15 channel sound waves are directed towards the focus position in respect of that input signal.

69. An apparatus according to claim 68, wherein said controller further comprises:

20 calculation means for calculating the respective delays in respect of each input signal replica by:

determining the distance between each output transducer and the focus position in respect of that input signal;

deriving respective delay values such that the sound waves from each  
25 transducer for a single channel arrive at said focus position simultaneously.

70. An apparatus according to claims 68 or 69, wherein said surfaces are reflective and have a roughness on the scale of the wavelength of sound frequency it is desired to diffusely reflect.



71. An apparatus according to any one of claims 68 to 70, wherein said surfaces are optically-transparent.

72. An apparatus according to any one of claims 68 to 71, wherein at least  
5 one of said surfaces is a wall of a room or other permanent structure.

73. A method of selecting a direction in which to focus sound, said method comprising;  
pointing a video camera in the desired direction, using the viewfinder or other  
10 screen means to determine if the direction is that desired;  
calculating a plurality of signal delays to be applied to a set of replicas of an input signal so as to direct sound in the selected direction.

74. A method of determining where sound is directed, said method  
15 comprising:  
automatically adjusting the direction in which a video camera points in accordance with the direction in which sound is directed;  
discerning from the viewfinder or other screen means which direction the camera is pointing in.

20

75. A method according to claim 73 or 74, wherein said sound is focussed and said camera is arranged to be focussed at the same position as said sound.

76. A method according to claim 73 or 74, wherein said sound is focussed  
25 using reference points in the room.

77. An apparatus for setting up or monitoring a sound field comprising:  
an array of output transducers;  
a directable video camera;  
30 means controlling said array of output transducers and said video camera such

that said video camera points in the same direction as a sound beam from said array is directed.

78. An apparatus according to claim 77, wherein said camera is attached  
5 to said array.

79. An apparatus according to claim 77 or 78, wherein said sound beam is arranged to be focussed and said camera is arranged to be focussed at substantially the same point.  
10

80. An apparatus according to claim 77 or 79, wherein said sound beam is arranged to be focussed at a reference point within the camera's field of view.

Fig. 1.

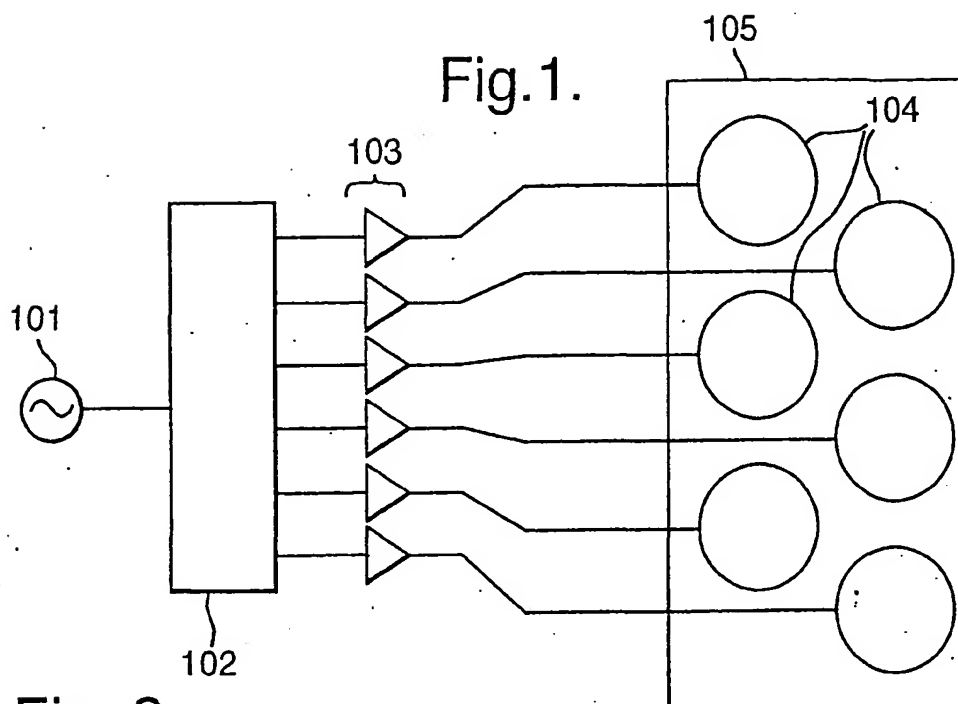


Fig. 2

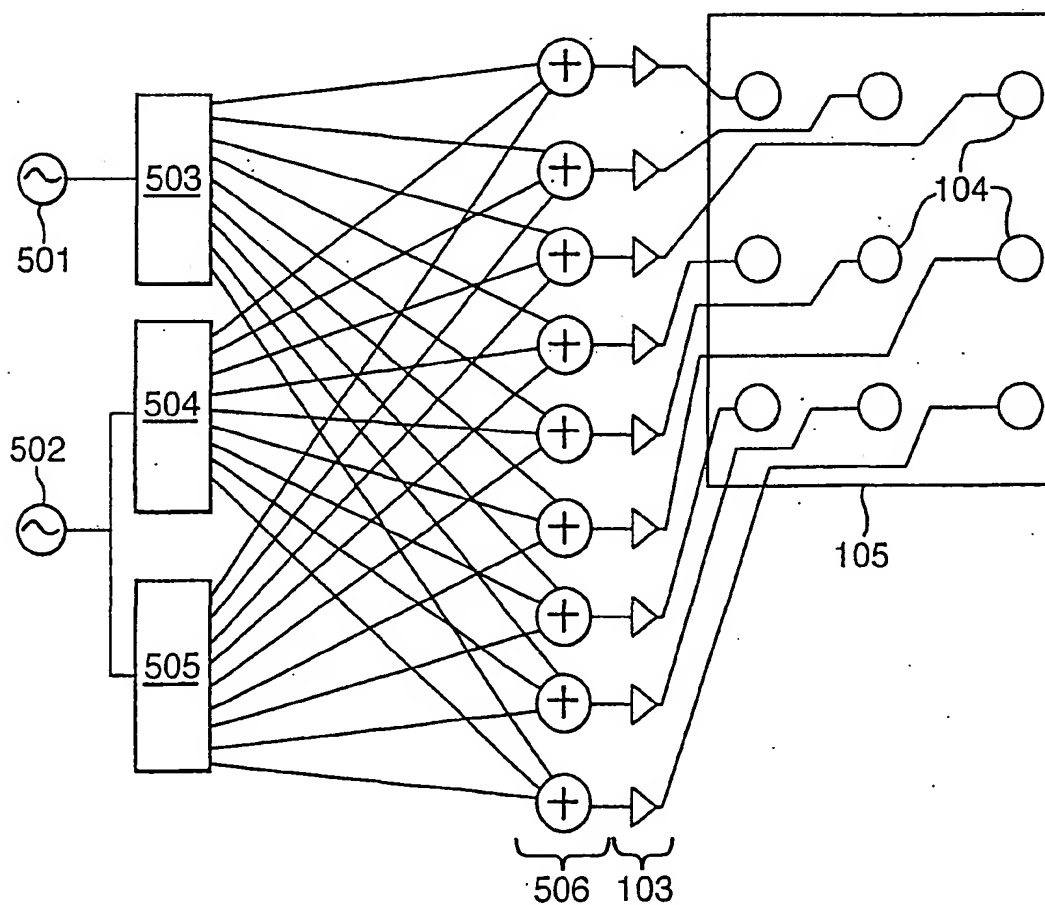


Fig. 3

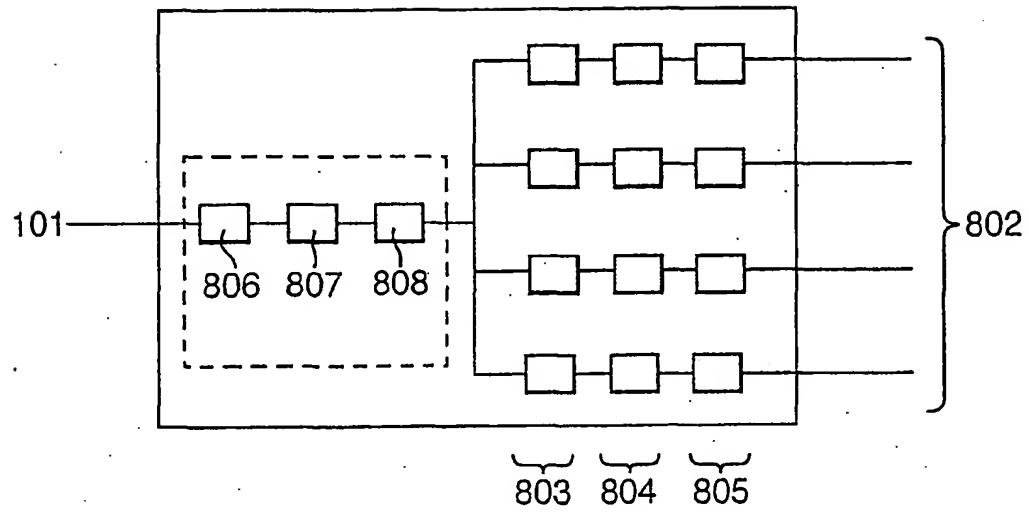


Fig. 4

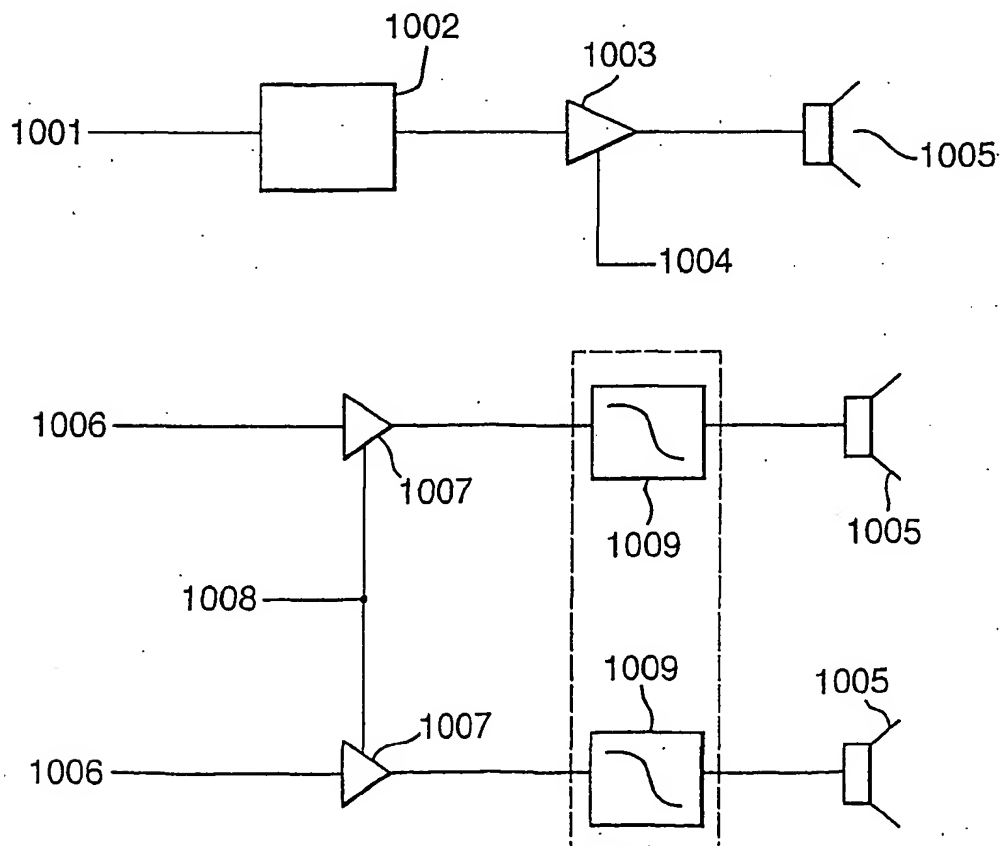


Fig. 5

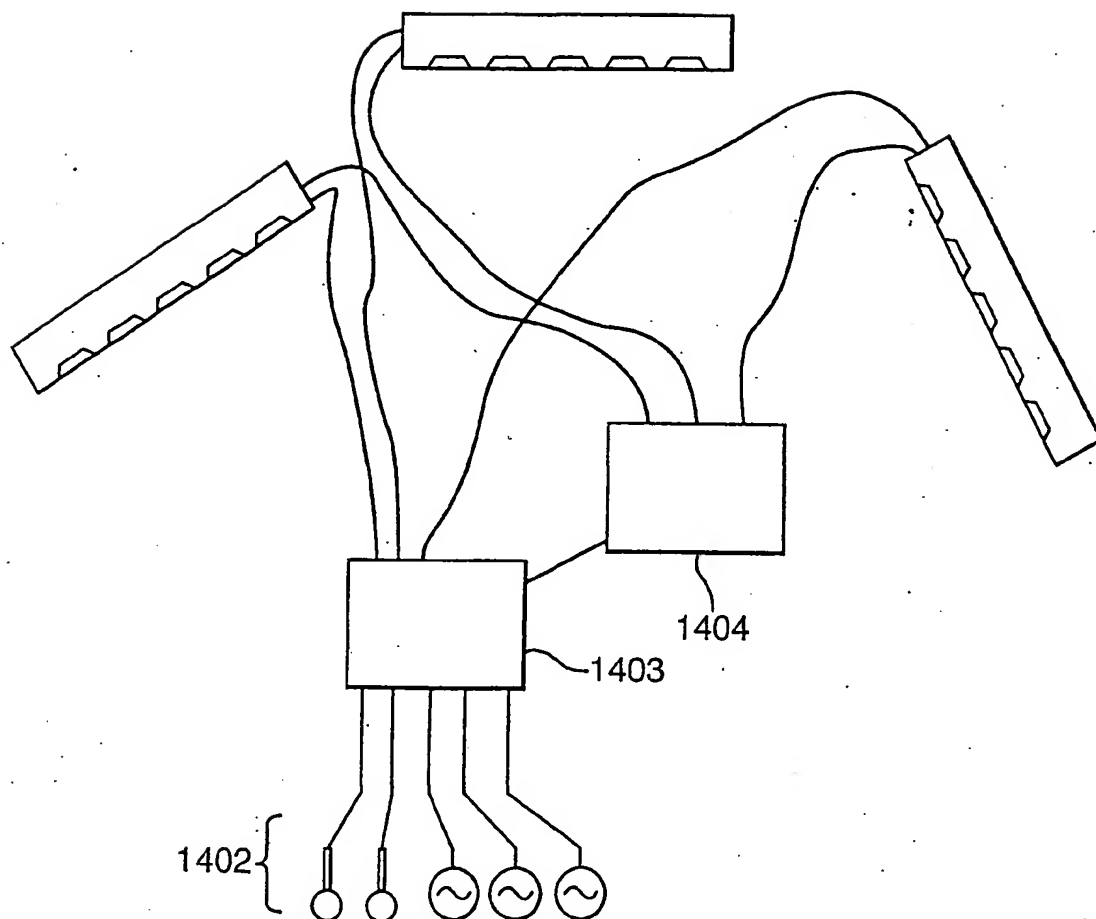


Fig. 6

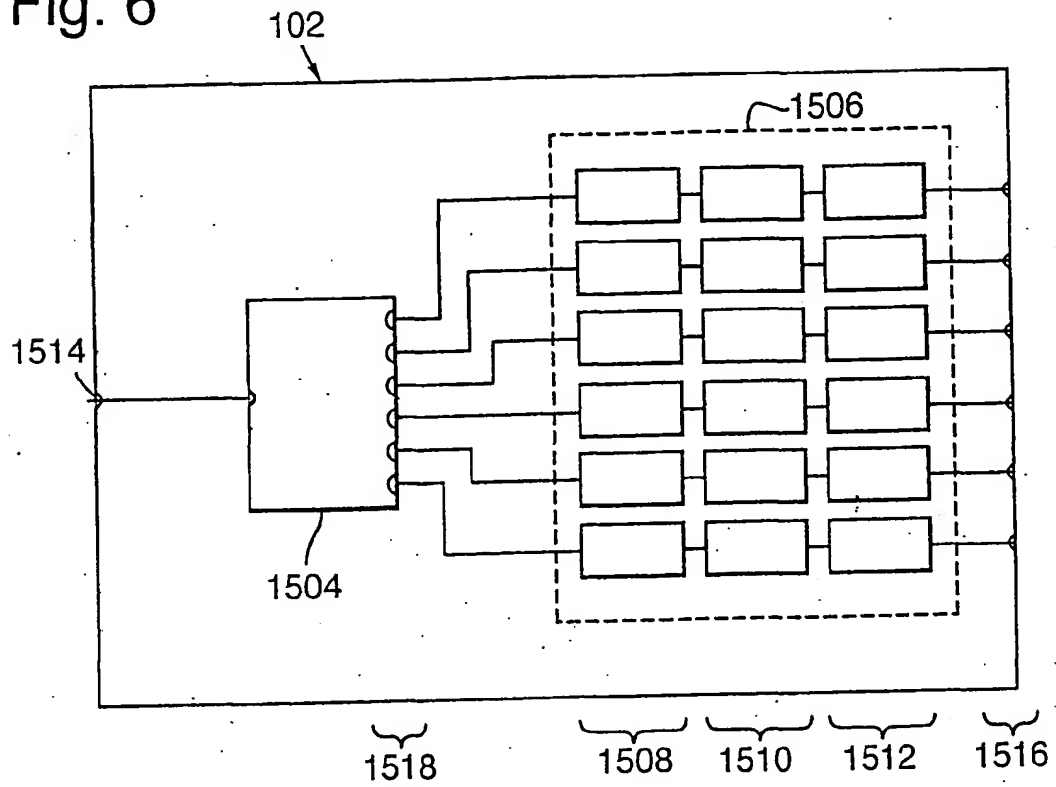


Fig. 7A

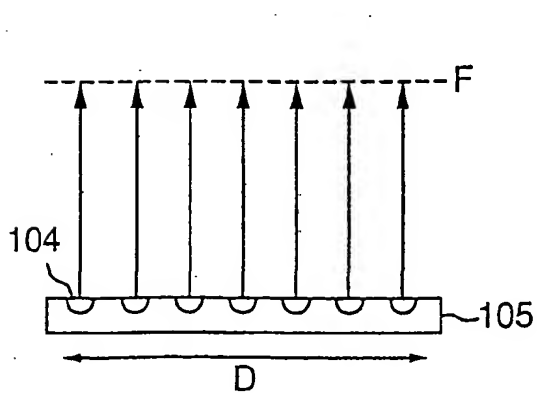


Fig. 7B

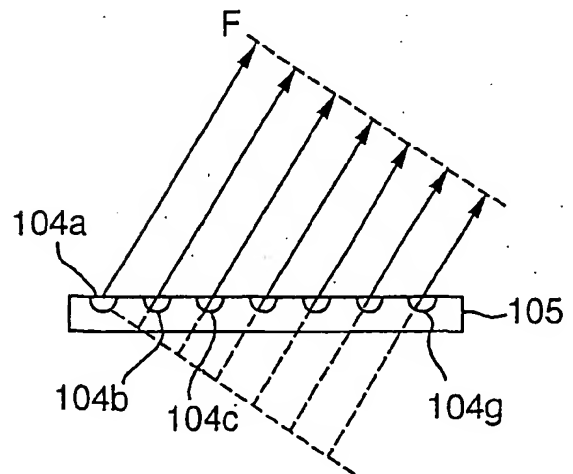


Fig. 7C

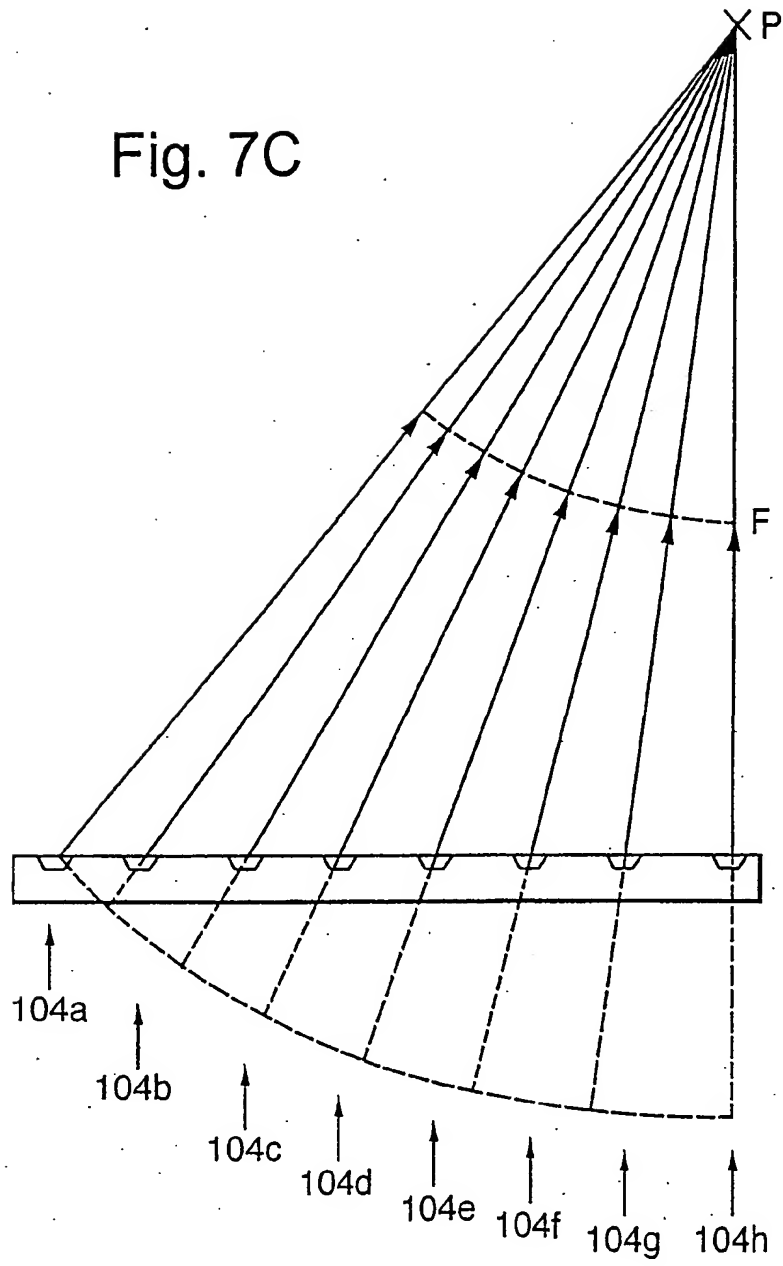


Fig. 7D

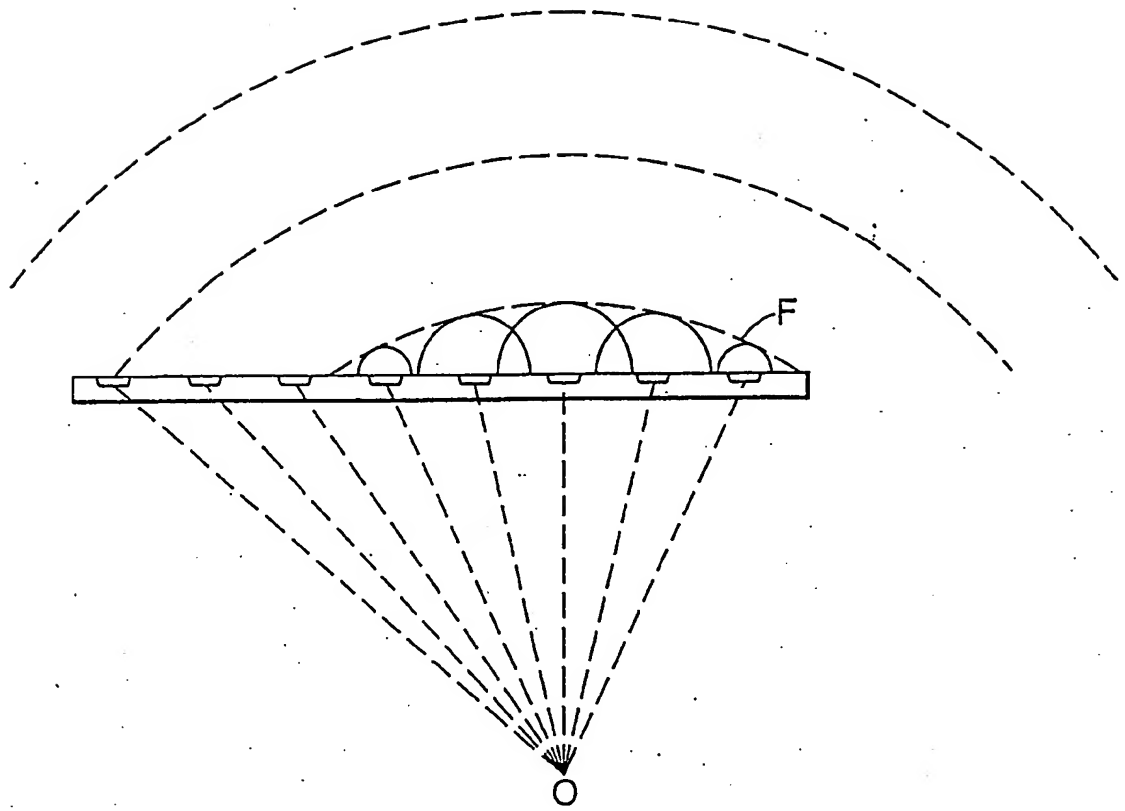




Fig. 8

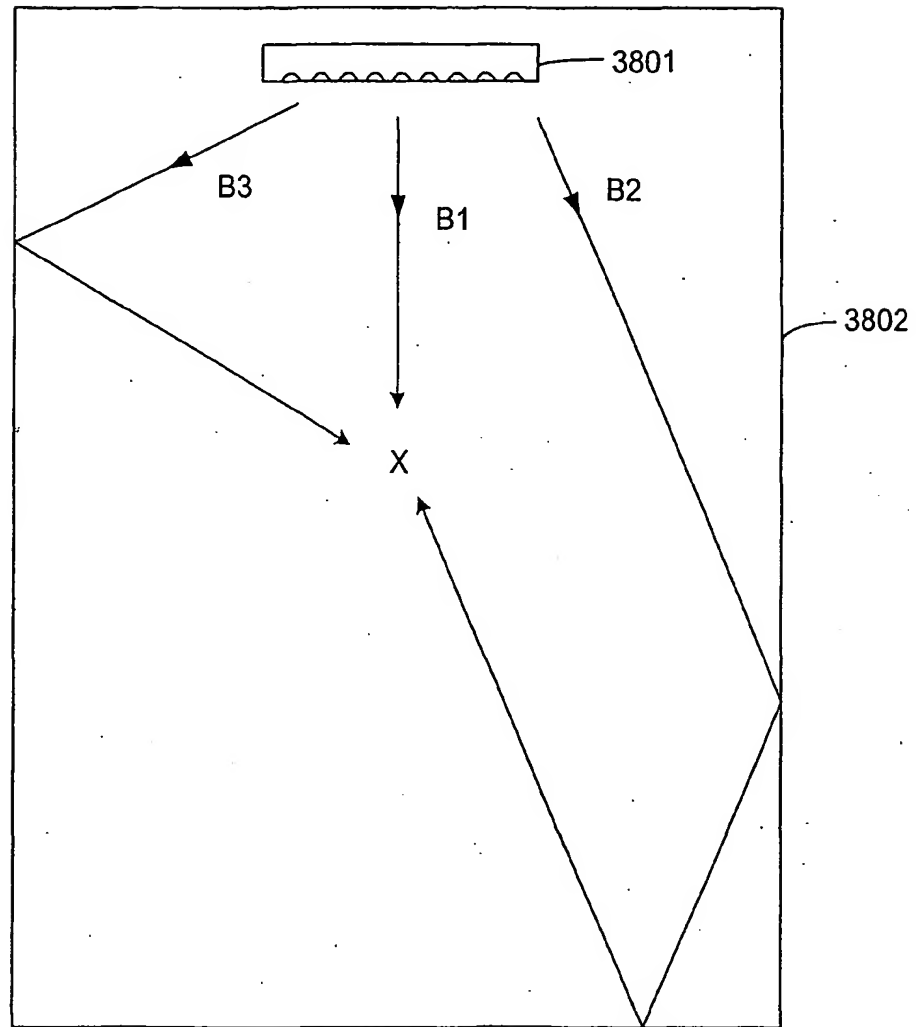


Fig. 9

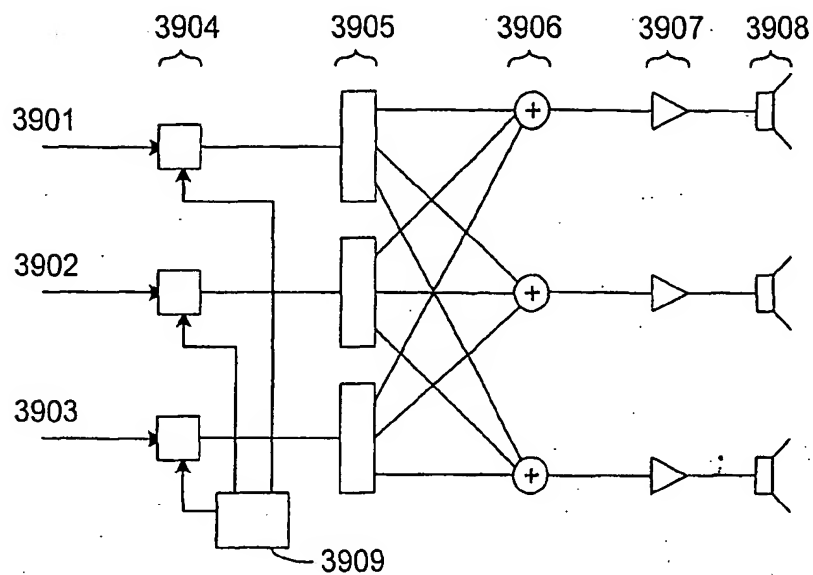


Fig. 10

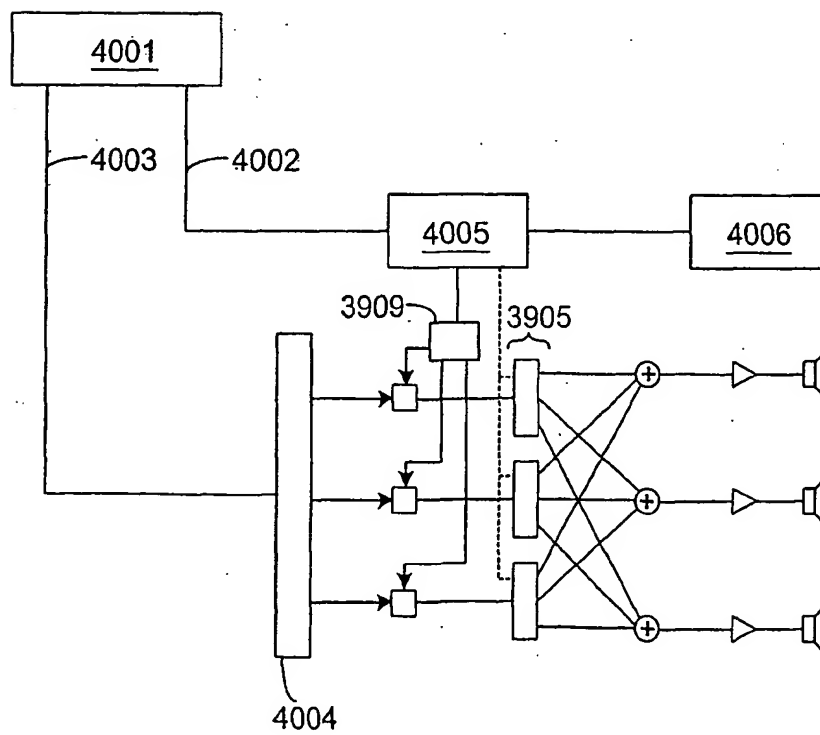


Fig. 11A

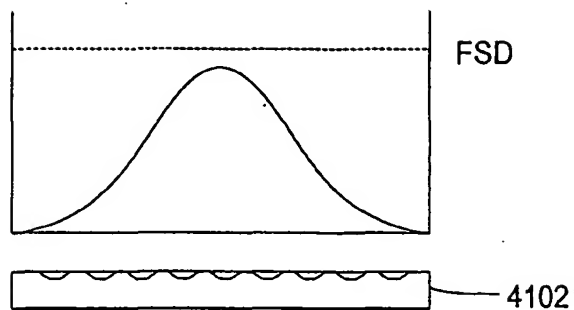


Fig. 11B

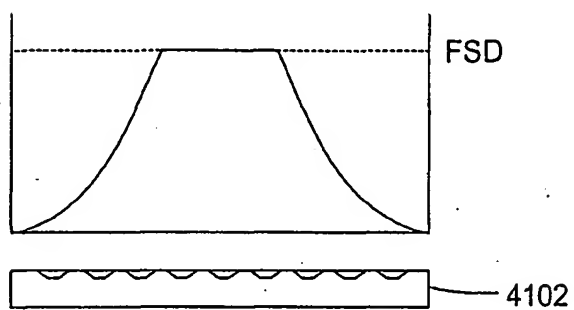


Fig. 11C

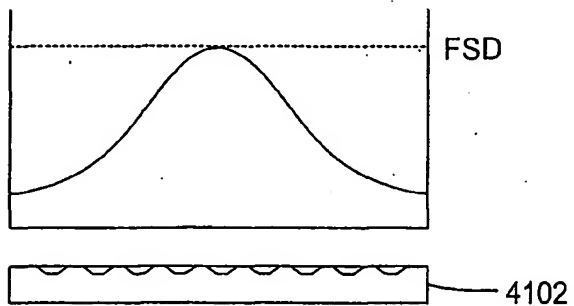


Fig. 11D

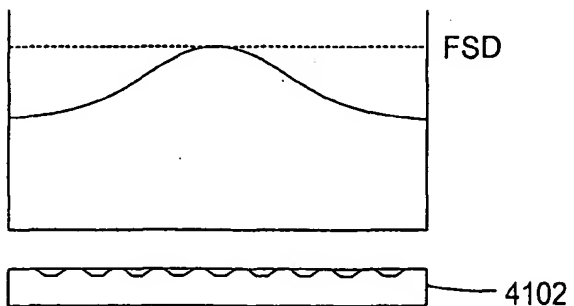


Fig. 12

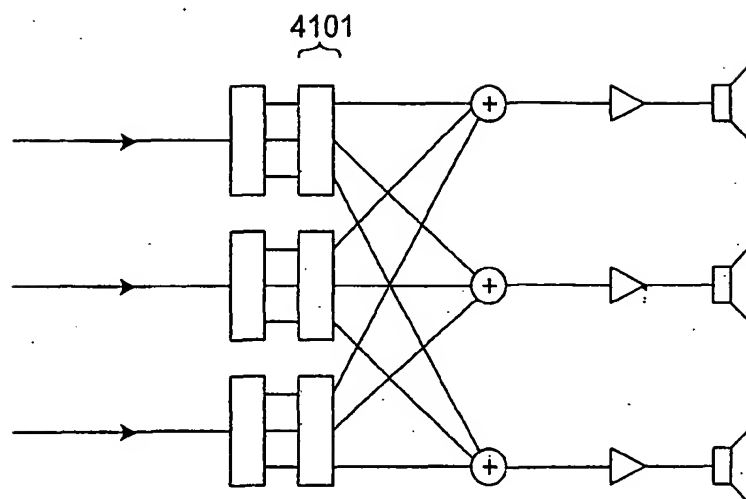


Fig. 13

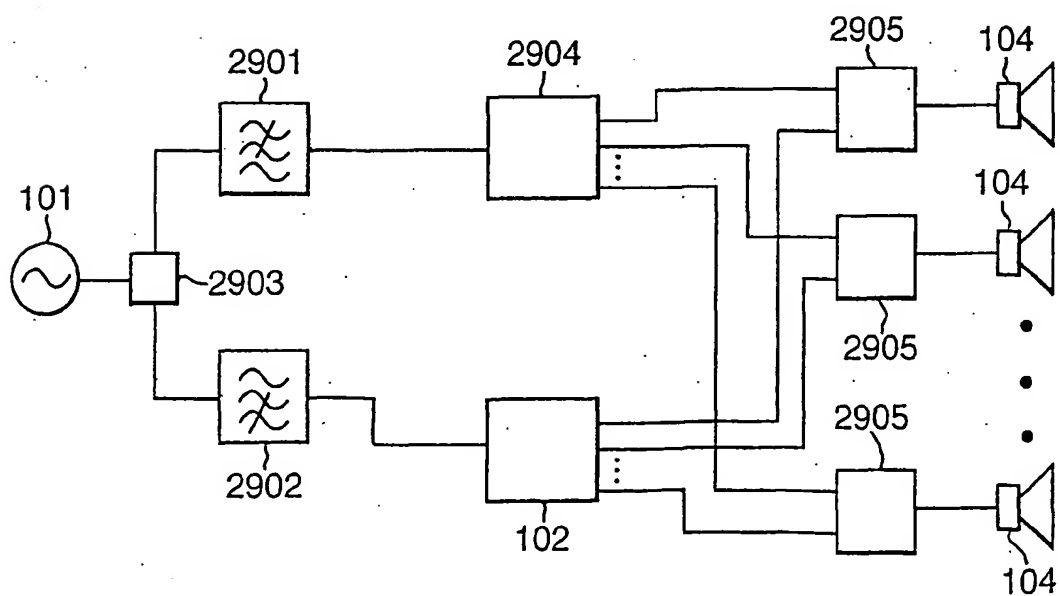


Fig. 14

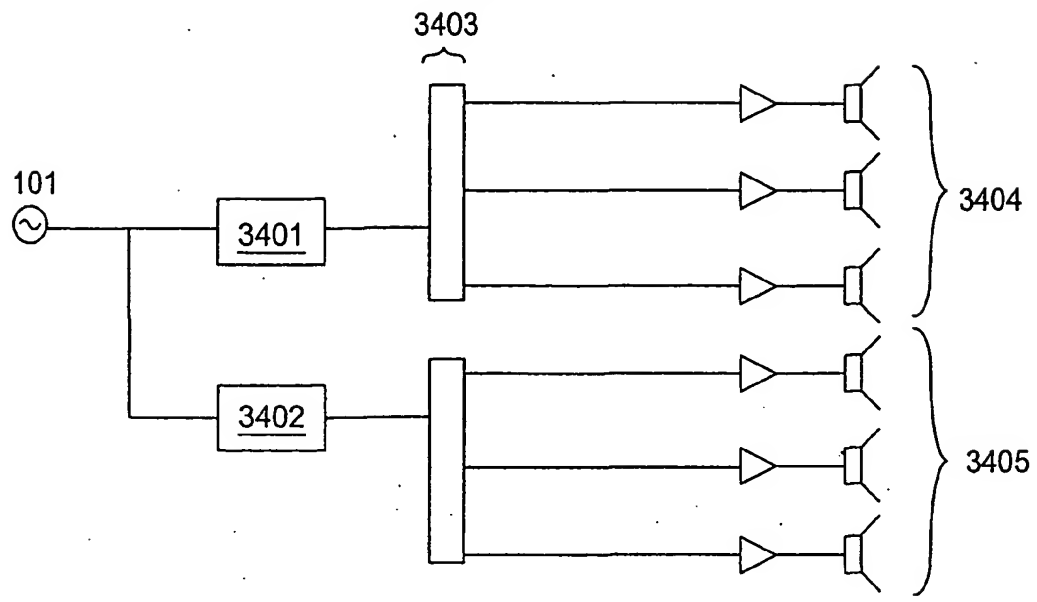


Fig. 15

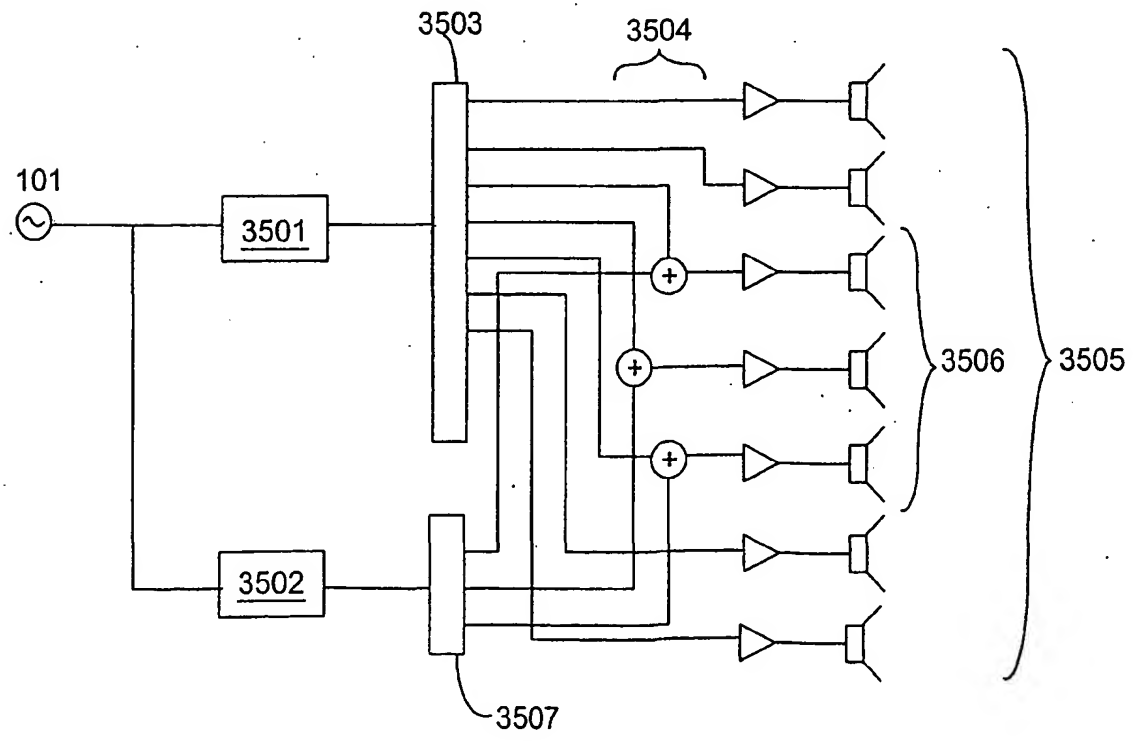


Fig. 16

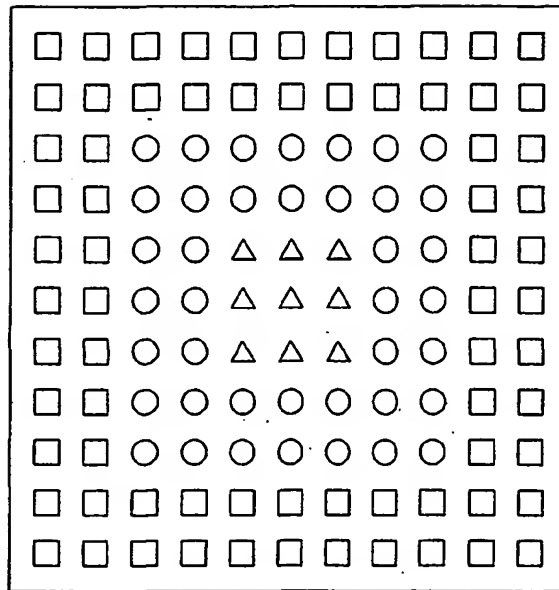


Fig. 17

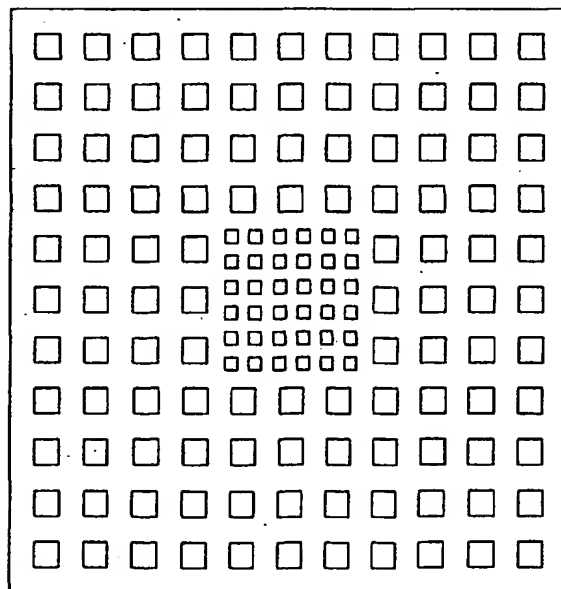


Fig. 18

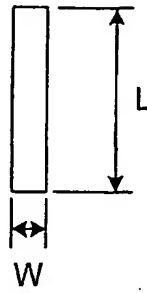


Fig. 19

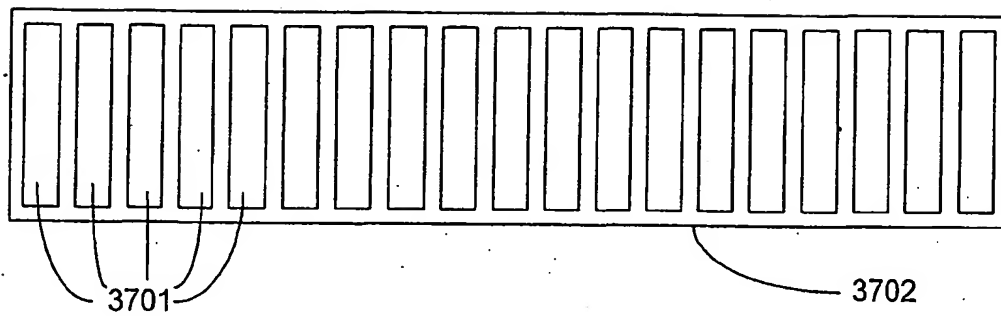
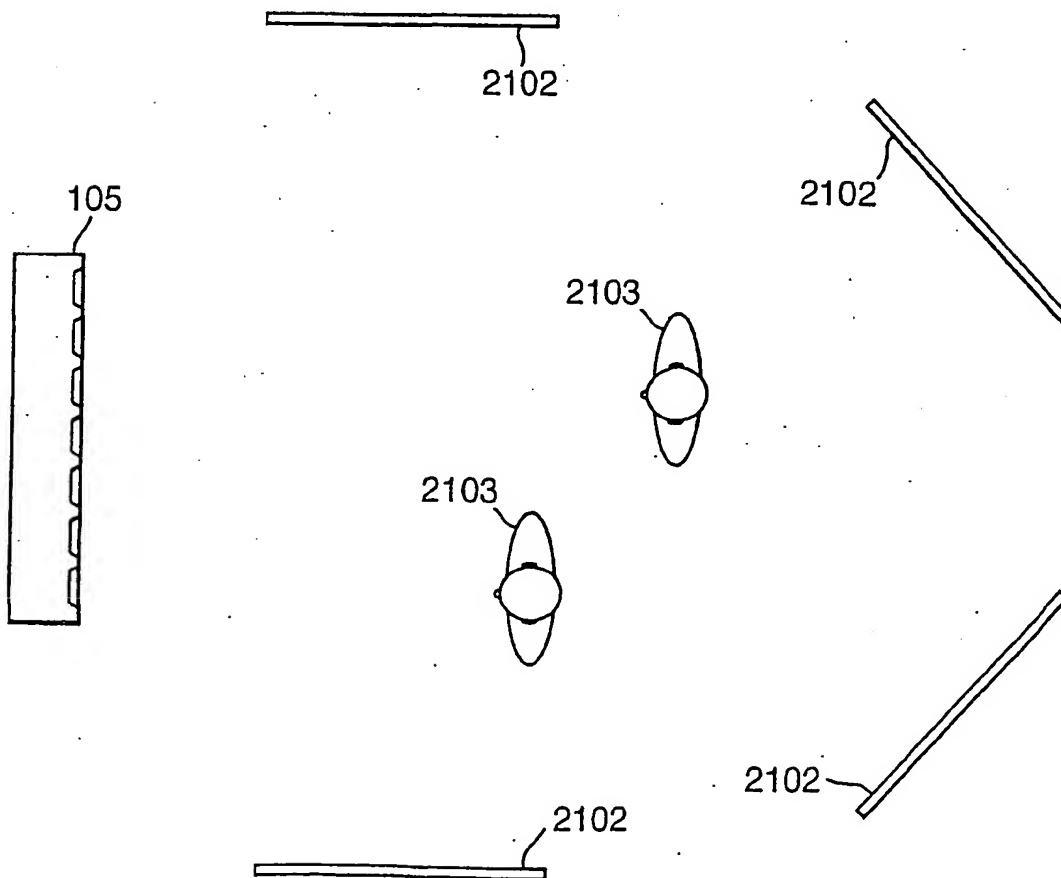


Fig. 20



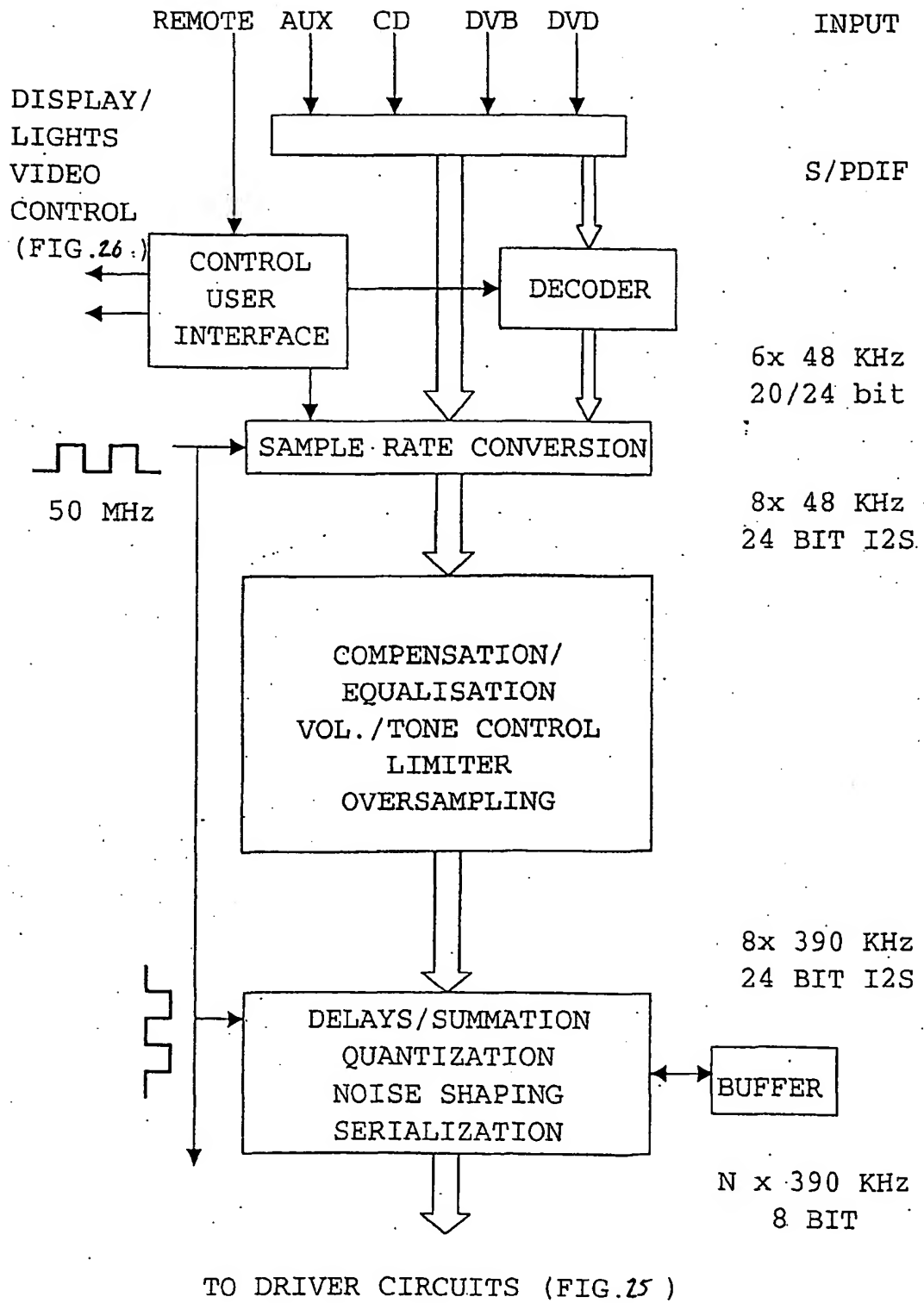


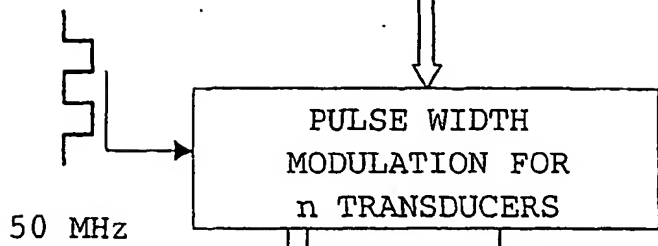
Fig. 24



17/18

FROM MAIN BOARD  
(FIG. 23)

$n \times 390 \text{ KHz}$   
8 BIT



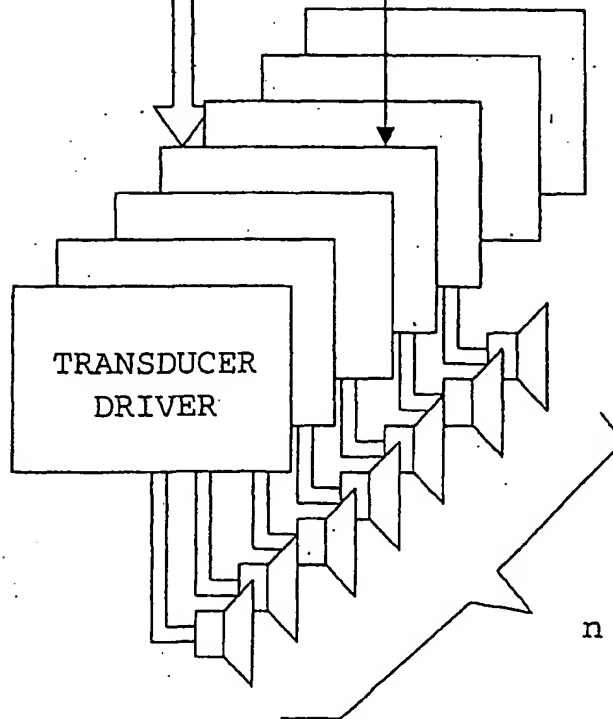
50 MHz

VOLUME  
CONTROL

TRANSDUCER  
POWER SUPPLY/  
SWITCH

Fig. 25

50 MHz  
PWM BIT  
RATE



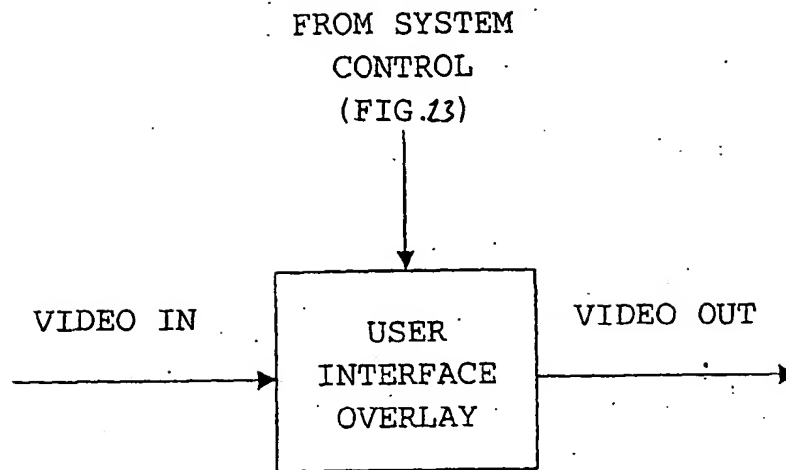


Fig. 26